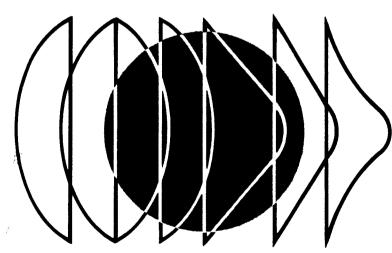
PART B2 ALTERNATIVES, ANALYSES, SELECTION

VOYAGER CAPSULE PHASE B FINAL REPORT



VOLUME III SURFACE LABORATORY SYSTEM

PREPARED FOR:
CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA
CONTRACT NUMBER 952000

COPY NO. 43

MCDONNELL ASTRONAUTICS

REPORT ORGANIZATION .

VOYAGER PHASE B FINAL REPORT

The results of the Phase B Voyager Flight Capsule study are organized into several volumes. These are:

Volume I Summary

Volume II Capsule Bus System

Volume III Surface Laboratory System

Volume IV Entry Science Package

Volume V System Interfaces

Volume VI Implementation

This volume, Volume III, describes the McDonnell Douglas preferred design for the Surface Laboratory System. It is arranged in 5 parts, A through E, and bound in 8 separate documents, as noted below.

Part A	Preferred Design Concept	1 document
Part B	Alternatives, Analyses, Selection	3 documents, Parts B_1 ,
Part C	Subsystem Functional Descriptions	$^{\mathrm{B}}_{2}$ and $^{\mathrm{B}}_{3}$ 2 documents, Parts $^{\mathrm{C}}_{1}$
		and $^{\rm C}_2$
Part D	Operational Support Equipment	1 document
Part E	Reliability	l document

In order to assist the reader in finding specific material relating to the Surface Laboratory System, Figure 1 cross indexes broadly selected subject matter, at the system and subsystem level, through all volumes.

VOLUME III CROSS REFERENCE INDEX

		PART A	APPENDIX A (TO PART A)	APPENDIX B (TO PART A)	PART B	PART C	PART D	PART E
SYSTEM/SUB	VOLUME III PARTS	PREFERRED DESIGN CONCEPT Objectives, Constraints — System Description, Sequence of Operations, Subsystem Summaries.	ENVIRONMENTAL REQUIREMENTS	FUTURE MISSION CONSIDERATIONS	ALTERNATIVES, ANALYSIS, AND SELECTION Trade Studies, Supporting Analyses, and Results	SLS FUNCTIONAL DESCRIPTIONS Subsystem Descriptions	OPERATIONAL SUPPORT EQUIPMENT	RELIABILITY Constraints, Analysis, Results Testing and Control
Surface	Laboratory System							
_	Objectives	Section 1	1.1 Environmental Design Criteria	1.1 Exploration Strategies	_	-	1. Introduction & Objectives	-
Mission	Constraints	Section 2	1.1 Environmental Design Criteria	1.1 Exploration Strategies	-	-	2. Requirements & Constraints	1 — Reliability Constraints 4 — Program Requirements
	Profile	Section 3.1	1.5 Mission Environmental Conditions	1.2 Mission Profile	4.7 Extended Mission	_	-	-
	Operations	4.1 Sequence 4.2 Timeline 4.3 Contingency Modes	1.3 Source of Environmental Parameters	-	2 — Mission Analysis	_	8. Software	2 — Failure Mode, Effects, Criticality Analysis 3 — Quantitative Estimates
Design	General	3.2 Configuration	1.2 General 1.4 Environmental Design Requirements	-	Study Approach & Analysis System Functional Requirements Major Trade Studies	-	3. Preferred Approach 3.2 Design Concept 6 — ASHE & Servicing Equipment 7 — SC Mounted SLS Equipment 10. Analyses & Trade Studies	5 – Component Part Reliability
	Standardization/Growth	11 – Summary	-	-	-	-	4.3.8, 4.5.8	
	Weight/Physical Characteristics	5 — Summary & Supporting Data	_	1.6 Constraints			4.3.3, 4.4.3, 4.5.3	_
	Reliability	6 — Philosophy, Implementa- tion, Definitions	-	-	4.6 Resource Allocation	•	4.3.6, 4.4.6, 4.5.6	-
Plane	etary Quarantine	7 - Contamination Analysis,	1.6 Sterilization & Decontami-	_	_	-	_	
	OSE	Design for Sterility 8 — General Description	nation _	-	-	-	Complete OSE Description 3.3 Equipment Summary 4 — System Level Support Equipment 4.3 STC 4.4 LCE 4.5 MDE	-
	s (Also See Volume V)	9 — System Interface Summary	_	-	_	-	4.3.5, 4.4.5, 4.5.5	_
	pplementation See Volume VI)	10 — Schedule & Program Summary	-	-	-	-	4.3.7, 4.4.7, 4.5.7	-
Ма	or Subsystems	Section 3.3	-	-	4.3 Analysis of SL Alternatives 5 — Subsystem Studies	Complete Subsystem Func- tional Descriptions	5 - SL Subsystems Level Test Equipment 5.9 Automatic Processor 5.10 Miscellaneous 9. Equipment Summary	-
Ele	ectrical Power	3.3.1 — Requirements, Equip- ment Description & Operation	-	1.4 Major Considerations	5.1 Power Studies	Section 1	5.3 EPS Test Set	See Part C - Section 1
	Sequencer	3.3.2 — Requirements & Description	-	-	4.4 In-Flight Monitoring & Checkout 5.2 Sequencing & Timing Studies	2.1 Sequencer & Timer 2.2 Test Programmer	5.4 Sequencer Subsystem Test Set	See Part C — Section 2
	Control	3.3.3 — Requirements & Description	_	-	5.3 High Gain Antenna Pointing Studies	Section 3	-	See Part C - Section 3
Tele	Communications	3.3.4 — Requirements & Description	-	-	5.4 Telecommunications Studies	4. Radio Subsystem 5. Antenna Subsystem 6. Command Subsystem 7. Telemetry Subsystem 8. Data Storage Subsystem	5.5 TCM Test Set	See Part C – Sections 4, 5, 6, 7, and 8
Structure (1	ncluding Mechanisms)	3.3.5 - Regmts & Description 3.3.5.6 - Mechanisms	-	-	4.2 Leveling 5.5 Structural/Mechanical	9. Structure 10. Mechanical	-	See Part C — Sections 9, 10
	Pyrotechnic	3.3.6 — Requirements & Description	-	-	Section 5,6	Section 11	5.8 Pyro Initiation Test Set	See Part C - Section 11
Pack	ging and Cabling	3.3.7 - Description	-		Section 5.7	Section 12	_	See Part C - Section 12
TH	nermal Control	3.3.8 - Description	-	1.5 Major Considerations	Section 5.8	Section 13	5.7 TCS Test Set	See Part C - Section 13
	Science	3.3.9 — Sequence & Description 3.3.9.4 — Integration	_	Major Considerations Stationary Laboratories Extended Sample Gathering Mobile Laboratories Mobile Systems Performance	4.1 Science Integration 4.5 Independent Data Package Study 5.9.1 Science Data Subsystem 5.9.2 Sample Acquisition & Processing	14.1 Science Data Subsystem 14.2 Sample Acquisition & Processing Equipment 14.3 Science Instruments	5.6 Science Test Set	See Part C — Section 14

Figure 1 // - 2

TABLE OF CONTENTS

	<u>Page</u>
PART B ALTERNATIVES, ANALYSES, SELECTION	
SECTION 5 SUBSYSTEM ANALYSIS	5–1
5.1 Electrical Power Subsystem	5.1-1
5.2 Sequencing and Timing	5.2-1
5.3 Control Subsystem High-Gain Antenna	5.3-1
5.4 Telecommunications	5.4-1
This Document Consists of the	Following Pages
Title Page	
i through iii	
PART B: 5-1	
5.1-1 t	hrough 5.1-33
5.2-1 t	hrough 5.2-18
5.3-1 t	hrough 5.3-11
5.4-1 t	hrough 5.4-150

SECTION 5

SUBSYSTEM ANALYSIS

Subsystem analysis has been a major element of our preferred design selection. In addition to the subsystem analysis to support the systems studies described in Section 4, there have been two types of studies of the subsystems themselves. First, trade studies to determine the preferred subsystem approach from among several candidates were conducted. Second, analyses to size and optimize the subsystem were performed. The preferred subsystem configuration is the one that yields an optimum Surface Laboratory System. To assure consistent judgement at every step of the analysis, the system-oriented analytical procedure described in Section 1 has been used in the subsystem analyses. The selection criteria which we used are:

- a. Probability of Mission Success
- b. System Performance
- c. Development Risk
- d. Versatility
- e. Cost

In our Phase B effort, the selection from alternate concepts, subsystems, and components has been conducted within technical disciplines but with extensive interdisciplinary coordination. For example, to achieve a Surface Laboratory configuration, repetitive refinements between configuration, thermal control, power, science and telecommunication took place in order to derive the preferred design for the Surface Laboratory.

The description of the subsystems and the alternatives for each selection has been made as comprehensive as practicable. Where alternatives were of nearly equal value, insofar as was possible, they have been given similar treatment. Emphasis has been placed on the rationale associated with choosing the preferred concept; i.e., how the selected concept best matched the stated requirements.

In the descriptions of the studies, certain subsystems (telecommunications, science, and thermal control) received particularly heavy emphasis. In the cases of telecommunications and science, this was due to the complexity of the tasks these subsystems are required to perform. Thermal control required particular emphasis because of its profound effect on the entire Surface Laboratory.

- 5.1 ELECTRICAL POWER SUBSYSTEM Various studies were performed in formulating the electrical power subsystem for the 1973 VOYAGER Surface Laboratory. The investigation, analyses, and conclusions leading to the selection of a preferred approach to the electrical power subsystem are briefly described herein.
- 5.1.1 <u>Summary</u> Four trade studies were performed in support of the SL electrical power subsystem. The major study was the evaluation of power source alternatives resulting in the selection of a battery system. The other three studies, battery charging method, power grounding method, and power conditioning method, were predicated on the selection of the power source. The float charge method of battery charging was selected to enhance battery performance. A single ground point was selected to provide assurance of electromagnetic compatibility on future missions. The decentralized power conditioning system was selected to provide adequate flexibility and minimize electromagnetic interference.
- 5.1.2 Power Source Study Three criteria are required of the electrical power system: sustained electrical power output of 290 watts, peak electrical power output of 338 watts, and electrical capacity of 4700 watt-hours (4450 watt-hours for equipment plus 6% distribution loss). A power profile for the baseline mission is shown in Figure 5.1-1. Due to battery internal losses, 4700watt-hours of useable electrical energy output produce 5400 watt-hours of thermal energy dissipation. An additional 3900 watt-hours of thermal energy is required for thermal contingency. This energy may be produced from an electrical, radioisotope, or chemical energy source, or from some combination of these sources. By the thermal study of Section 5.8, the thermal energy contingency is supplied by the electrical power source to provide control of the heat production, and to provide mission extension should the energy contingency not be required for thermal control. For a detailed discussion of the thermal control study, see Section 5.8.
- 5.1.2.1 Alternate Approaches Candidate power sources to provide the electrical power and energy requirements and the thermal energy requirement of the Surface Laboratory are: Fuel Cells, Battery, Radioisotope Thermoelectric Generator (RTG), RTG with Battery, and Solar Cells with Battery. The following paragraphs discuss the salient features of each power source candidate.

Solar Cell-Battery - Blowing dust, wind gusts, and continuous overcast present

SL ELECTRICAL POWER SUBSYSTEM POWER PROFILE

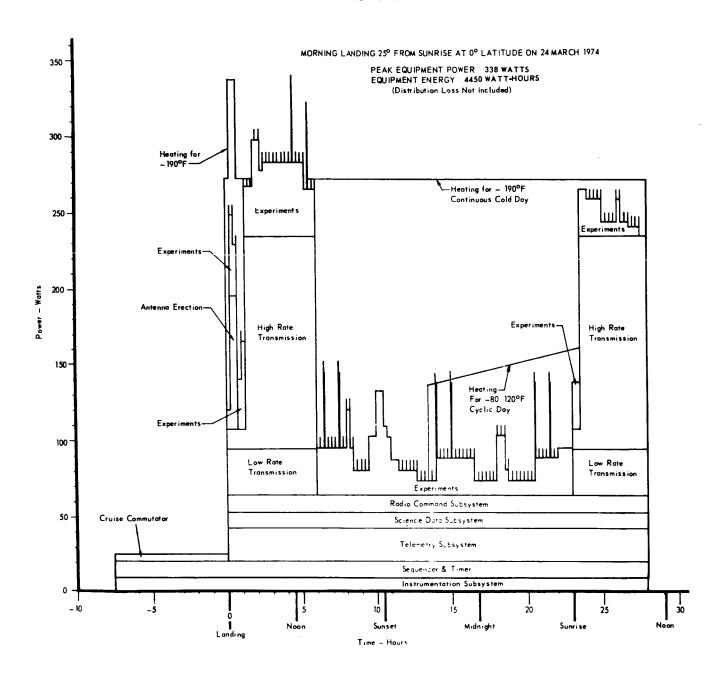


Figure 5.1-1

an environment hostile to the effective operation of solar cell panels. The actual extent and probability of these dust, wind, and cloud conditions cannot be adequately defined for the initial VOYAGER mission. Therefore, any solar cell system requires a battery power source of sufficient size to complete the basic mission without a contribution from the solar cells.

To provide the 4700 watt hours required by the SL electrical equipment over the 28 hour mission baseline period requires a tracking array area of 198 square feet for 20° N latitude and an area of 241 square feet for 40° S latitude with the Sun at 15° N latitude. These area figures do not take into account the electrical system inefficiencies to charge batteries. The solar cell area requirement significantly increases for a fixed array, and at 40° S latitude a fixed array, with its normal perpendicular to a local slope at 34° away from the sun, produces no output. These area requirements are incompatible with the 1973 VOYAGER spacecraft.

The area requirement and auxiliary battery requirement for continuous cloud cover, precludes the use of solar cell arrays as the power source for the initial VOYAGER mission. However, should the environment prove favorable and degradation reasonable, solar cells may present an excellent approach for mission extension applications.

<u>Fuel Cell</u> - The advantages, disadvantages, and other significant factors of fuel cell power sources are summarized in Figure 5.1-2. The major factors influencing a fuel cell selection are weight, sterilization, and local contamination of Martian environment.

There are three major companies in the fuel cell field: General Electric,
Pratt and Whitney, and Allis-Chalmers. Each of these companies uses a different
approach in the construction of the fuel cell. The Genral Electric ion exchange
membrane type fuel cell would probably not be suited for this application, since
the membranes employed are sensitive to elevated temperatures and probably would
be damaged by sterilization. The Pratt and Whitney approach for 1.5 kilowatt
units utilizes highly concentrated potassium hydroxide and operates at 400°F.
Therefore, this fuel cell stack is certainly capable of being sterilized. The
Allis-Chalmers approach, and the Pratt and Whitney approach for low power units,
employ capillary asbestos membranes, and the cells operate at approximately 200°F
with limited performance at 250°F. The manufacturers indicate that the basic stack
components should not be affected by the sterilization temperature, and therefore
are potentially sterilizable. All of the fuel cells employ auxiliary equipment,
valves, regulators, and water removal systems that would have to be evaluated

FUEL CELL POWER SOURCE CHARACTERISTICS

ADVANTAGES	DISADVANTAGES	OTHER FACTORS	
Lowest Weight for Short Missions (4—30 KWH)	Limited Power Output Fixed by Design Size	Requires High Pressure Gas Storage	
Heat Source for Cold Environment	Sterilization Not Demonstrated	Requires Minimum Operating Level	
Non-Magnetic	Environment Contamination	Moderate Heat Generation	
Excellent Reliability	by Purge Gases		
	Bulky Fuel Storage		
		Negligible Gas Leakage	
	Alternate Power Source Required During Transit	Moderately Expensive	
		Reasonable Development Requirement	

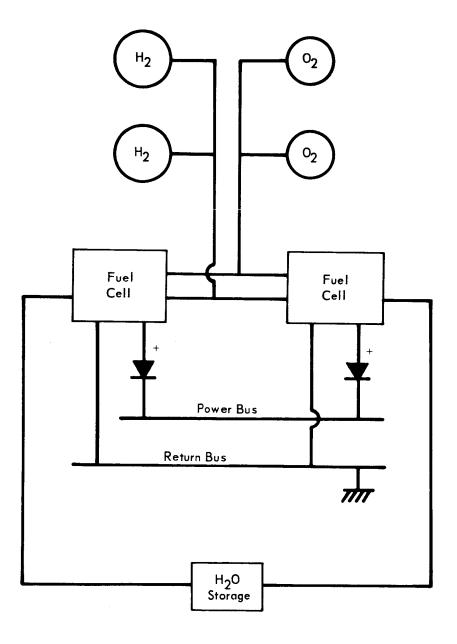
for sterilizable materials. Since a long transit period is involved, the reactants hydrogen and oxygen would necessarily have to be stored as compressed gases as opposed to cryogenic storage that is currently used on short duration missions. The use of compressed gas as the fuel and oxidant reduce the energy density capabilities of the unit. The Allis-Chalmers approach is considered the most favorable for use on the VOYAGER program and is therefore the basis for comparison.

The conceptual approach for the fuel cell system would be spherical pressurized hydrogen and oxygen gas tanks that would supply the reacting gases, through high pressure regulators, into the fuel cell input regulator. The initial pressure in the tanks would be 3000 psi and the pressure regulators would reduce this to approximately 150 psi at the input to the fuel cell unit regulators. The fuel cell regulators would provide the required cell matrix pressure. During transit the gas pressure storage vessels would be sealed, and an explosive device would be used to break a frangible diaphragm valve to initiate fuel cell operation. With this system there is no reactant loss during the transit phase. The regulators would automatically supply the reacting gases to the fuel cell stack as the load demands and maintain the stack pressure throughout the entire operating life. A typical fuel cell system is shown in Figure 5.1-3.

For the landed requirements, the fuel cell system would require a water storage tank to accept the reaction product water as the cell performs, to avoid flooding and consequent degradation in performance of the cell stack. Another approach would be to vent the water, as it is formed, through a pressure relief valve to the low pressure ambient on the Mars surface, and allow evaporation into the atmosphere. However, venting to the Mars atmosphere is considered objectionable to the mission requirements, and therefore is rejected.

A fuel cell system consisting of storage tanks, pressure regulators, fuel cell stack, and water removal devices is more complicated than a primary type battery, and this must be considered in selection of the power source. The concept of a capillary type fuel cell utilizing asbestos matrix with stored pressurized reactant gases simplifies many of the complexities of the earlier fuel cells. The 28 hours of the baseline mission is not a very rigorous application. Since the fuel cell is of module design, block redundancy, at only moderate weight penalties, is utilized for the entire cell stack. An actual reliability level cannot be ascribed to the system since insufficient test data is available, and the mission is complicated by sterilization.

FUEL CELL SYSTEM BLOCK DIAGRAM



The major criteria and considerations for the cell design is its potential sterilization. Capillary type fuel cells using an asbestos matrix can be constructed of components that are not affected by sterilization temperatures of $275^{\circ}F$. No major problems should be encountered in obtaining auxiliary components that are sterilizable. The reactant tankage weight allowance takes into consideration the pressure rise as a result of sealed gas storage at 3000 psia at $90^{\circ}F$ and the subsequent subjection to a 275° sterilization temperature. A burst pressure safety factor of 2.22 is used at $90^{\circ}F$ and reduces to 1.5 at $275^{\circ}F$.

The fuel cell is the lowest weight power source for a 4 to 30 kilowatt-hour energy requirement. The fuel, fuel storage tanks, and product tank are the variable weight dependent upon the energy requirement. Gas storage at 3000 psi in titanium tanks is used for comparing power sources. Light weight, aluminum lined, filament spun tanks will reduce the tankage weight by about 30 percent. This lighter weight tank design increases the fuel cell weight advantage such that it is the lowest weight system for a 3.5 to 45 kilowatt-hour energy requirement.

In order to obtain satisfactory performance from the fuel cell, the stack should be maintained at a temperature from 190° to 220°F. This is not considered a major problem as integration of an RTG imposes more severe thermal problems. The cooling requirements of the fuel cell system would be accomplished by the integral Surface Laboratory thermal control system. Heat pipes would be utilized to direct the fuel cell heat into the Surface Laboratory during cold periods. During warm periods, other heat pipes would direct the heat to external surface radiators. No weight penalty is taken into account for this heat transfer system in the fuel cell weight figure as no significant weight change is anticipated. For a detailed discussion of the thermal control problem, see Section 5.8.5.2.

Another fuel cell system is the lithium-clorine power source. It currently is quoted as offering a significant (2:1) weight advantage over the hydrogen-oxygen fuel cell system. For this reason it appears an attractive alternative, and the system is inherently sterilizable due to operating temperature of 650°C. Presently, however, only limited laboratory data is available, and no flight proven system has been developed. Many problems are yet to be solved including startup failure modes, self discharging after activation, and the effect of clorine on storage vessels at sterilization temperature or for long durations. With this system still in the initial development stage, it is impractical to base a 1973 VOYAGER mission upon this technology.

<u>Battery</u> - The advantages, disadvantages, and other factors for a battery power source are summarized in Figure 5.1-4. The major factors influencing a battery

5.1-7

BATTERY POWER SOURCE CHARACTERISTICS

ADVANTAGES	DISADVANTAGES	OTHER FACTORS
Minimum Volume	Heavy System for over 5 kwh Capacity	Acceptable Reliability
Minimum Dollar Cost	Sterilization Development Required	Sterilization Feasibility Demonstrated
Very High Peak Power Capability	Limited to Energy Capacity Design Size	Poor Voltage Regulation
Low Heat Generation at High Power Output	Capacity Loss on Wet Stand	Negligible Capacity Loss with Float Charging
No Effect on Environment		
Simple Electrical System	·	

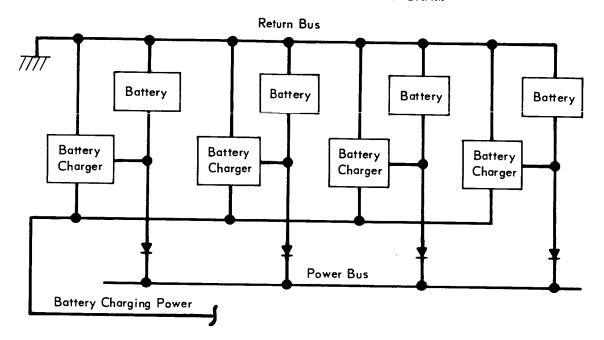
power source selection are system simplicity, dollar cost, contamination of the Martian surface, and sterilization.

A battery system is the simplest candidate system as no auxiliary equipment is required for usable output power. However, a battery charger has been included to enhance the total battery performance and maintain full battery capacity during long wet stand periods rather than incur the weight penalty of providing excess initial capacity to account for wet stand losses. Further, to insure partial mission success - no single point failure - functional redundance is assumed, i.e., the total energy requirement is divided into multiple individual battery packages. The penalty for the use of this method of redundancy is reduced total mission reliability. Figure 5.1-5 shows the battery power source system divided into four battery packages per the selected baseline design.

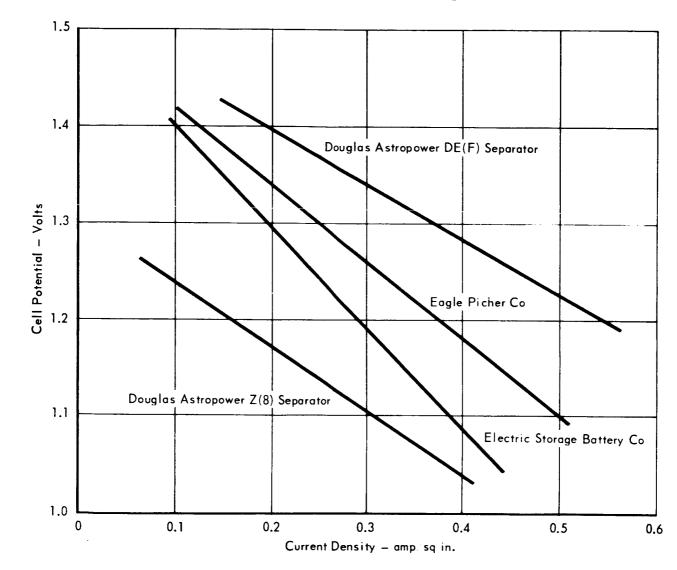
Review of development work on sterilizable, long wet life, silver-zinc batteries indicates significant advances have been made in the technology. Three companies, Eagle-Picher, Electric Storage Battery, and Douglas Astropower Laboratory, are currently developing heat sterilizable, long wet life batteries. Polarization curves for these cells are shown in Figure 5.1-6 along with a polarization curve of a Douglas Astropower Laboratory cell utilizing a new separation material, DE(F), which gives significantly higher performance capability. Testing of cells using the DE(F) separator is now in progress at Douglas Astropower. The design parameters of the cells subjected to heat sterilization testing are shown in Figure 5.1-7. A summary of the heat sterilization and wet stand tests performed to date is shown in Figure 5.1-8. These test results, although providing limited evidence of sterilizability of silver-zinc batteries, do show feasibility.

The energy density achieved in these tests batteries indicates that 30 to 38 watt-hours per pound is achievable with a discharge rate of C/4 (battery capacity in ampere-hours/discharge time in hours) on 8-ampere-hour batteries. Comparing unsterilizable silver-zinc battery data, scaling up capacity from 8 to 80 ampere-hours increases battery energy density by about 20%, and reducing discharge rates from C/4 to C/30 additionally increases battery energy density by about 10%. Extrapolating this scaling to sterilizable batteries, the 30 to 38 watt-hour per pound energy density of 8-ampere-hour batteries should yield an energy density of 40 to 50 watt-hours per pound for an 80-ampere-hour battery discharged at a C/30 rate. A conservative figure of 35 watt-hours per pound is assumed for Surface Laboratory battery weight computations. This allows some weight contingency in the battery which may be used in solving the remaining development problems.

BATTERY SYSTEM SCHEMATIC DIAGRAM



PLATEAU VOLTAGE OF STERILIZABLE AgZn CELLS



DESIGN PARAMETERS OF STERILIZABLE CELLS TESTED

MANUFACTURER DESIGN PARAMETERS	ESB MODEL 334	EAGLE PICHER	DOUGLAS ASTROPOWER
Capacity	40 amp hr	8 amp hr	2 amp hr
Separator	5-RA1-116	4 Pernion — 307	Inorganic — Z (8)
Cell Case	Polyphenylene Oxide	Polypropolene	Polyphenylene Oxide
Type of Cell	Sealed _.	Sealed - Pressure Relief	Sealed
Battery Case	_	Magnesium-Sealed	-
Cells/Battery	-	6	-
No. of Cells Tested	7	12	16
Operating Temperature	80°F	75°F	77°F

Figure 5.1-7

SUMMARY OF STERILIZABLE A_gZ_n CELL AND BATTERY TESTS

MANUFACTURER		EAGLE PI	CHER CO.	DOUGLAS
PERFORMANCE	ESB MODEL 334	BATTERY NO. 1	BATTERY NO. 2	ASTROPOWER
Sterilization Environment	135°C - 120 hr - 1 cycle	145°C – 36 h	r – 3 cycles	145°C - 36 hr - 3 cycles
Wet Stand Time	-	10 months	10 months	5 Months — 4 cells 3 months — 4 cells 2 months — 4 cells 1 month — 3 cells
Wet Sand Condition	-	Discharged	Charged	Charged
Discharge Rate	4 hr Rate to 1.3 v/cell; Then 8 hr Rate to 1.3 v/cell	4 hr Rate to 1.25 v/cell	4 hr Rate to 1.25 v/cell	7 hr Rate for 1 hr; Then 2.7 hr Rate to 1.0 v/cell
Energy Density	31.5 wh/lb	30 wh/lb	38 wh/lb	20.5 wh/lb*
Cycle Life Following Wet Stand (100% Depth)	-	2	16	2+

^{*} Projected for optimized battery design.

Radioisotope Thermoelectric Generator (RTG) - The advantages, disadvantages, and other significant factors of the RTG are summarized in Figure 5.1-9. The major factors influencing an RTG selection for the SL electrical power source are mission time, fuel availability, and reliability.

The nominal 89-year half life of Plutonium-238 results in a loss of only one-half percent per year. This essentially constant fuel output, plus the passive, fixed, mechanical structure provides a long life, very reliable power source. Addition of heat pipes to operate in a cyclic temperature environment reduces the reliability.

Plutonium-238 fuel availability is an important factor in the evaluation of an RTG power source for the 1973 VOYAGER mission. The fuel availability definition ultimately depends upon interactions between the VOYAGER program fuel requirements, the requirement of other radioisotope power programs, and the implemented fuel production capability. Classified fuel production capabilities giving an accurate, current picture are available in Reference 5.1-1. The long lead time of Plutonium-238 production requires early decision on fuel allocation and production requirements.

The inherently low radiation level associated with Plutonium-238 and the fuel capsule re-entry protection preclude major radiation problems and minimizes the personnel hazard. Plutonium-238 decay produces neutron radiation and some gamma radiation. However, the gamma production increases with time. For long-term missions, or extended storage prior to launch, the increased gamma radiation must be considered. Sensitive experiment equipment may require local shielding.

From a weight standpoint, the RTG is an attractive power source, since the design is dependent upon power output rather than energy output. However, for efficient utilization of the energy, the power requirements should fluctuate very little providing, ideally, identical peak and average power levels - constant power load. Since the weight is independent of energy requirements, in-transit energy, independent of spacecraft orientation, is available from this source.

An added feature for this fixed weight is the large continuous thermal energy available for equipment heating. This may be disadvantageous, as this heat must be continually rejected even in a cyclic temperature environment. This presents a thermal control problem to retain sufficient heat to keep equipment and the RTG warm during low temperature periods, yet reject the continuous, constant, heat output when the temperature rises. However, a very suitable environment is the cloudy, cold Martian surface or deep space. For Earth storage and launch opera-

RTG POWER SOURCE CHARACTERISTICS

ADVANTAGES	DISADVANTAGES	OTHER FACTORS
Very Long Mission Life Energy Output Independent of Weight Sterilizable In Transit Energy Source Heat Source High Reliability Minimum Power Output Degradation with Time Non-Magnetic	Expensive System and Fuel Limited Fuel Availability Power Output Fixed by Design Size Continuous High Thermal Output Neutron and Gamma Radiation Complex Electrical System	Reasonable Development Requirement Acceptable Weight Acceptable Volume

tions, present OSE for air cooling is adequate to allow RTG usage. A byproduct of the RTG thermal design is inherent heat sterilizability as operating temperatures exceed the sterilization requirements.

The electrical subsystem for the RTG power source is complex. A typical electrical subsystem block diagram is shown in Figure 5.1-10. In addition to the RTG, shunt regulators and DC-to-DC converter-regulators are required. The shunt regulator provides the desired, constant, RTG electrical load thereby preventing RTG temperature buildup when the using electrical and electronic equipment load is light; block redundancy is required. The DC-to-DC converter-regulator provides a nominal 28-volt, regulated potential from the low voltage unregulated RTG output; block redundancy is required.

Utilization of a basic SNAP-27, RTG design minimizes generator development for the VOYAGER program. A detailed discussion of VOYAGER RTG design derivations from the proven SNAP-27 generator design is found in Reference 5.1-2.

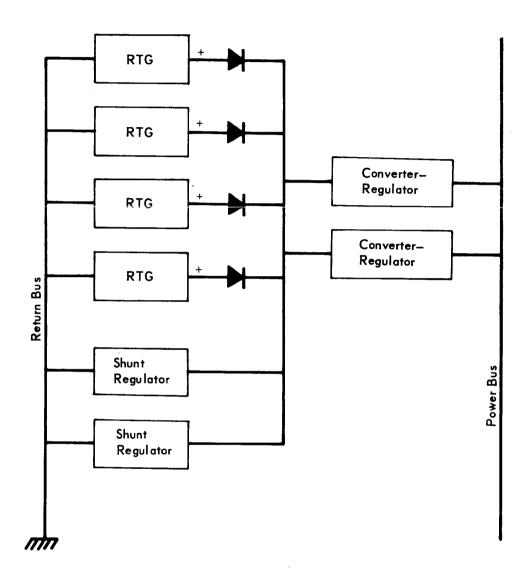
The RTG is an attractive electrical power source for missions of sufficient duration that batteries alone or fuel cells are exorbitantly heavy and into an environment hostile to solar cell operation. The key to RTG integration is the accommodation of the continuous heat dissipation requirement and the radiation emitted by the radioisotope fuel. Since the CB and SL are designed to accept an RTG source of up to 7 kilowatt-hours thermal for 1975-79 missions, inclusion in the 1973 mission requires minimum design perturbations.

The cost of the RTG and radioisotope fuel is far in excess of the cost of other power sources considered. A decision to use RTG must include a commitment to fully utilize its potential, i.e., design for a long duration mission. The cost for a short duration mission - a few days - is prohibitive, as other power sources are significantly less expensive and provide the mission requirement with equal or less weight and adequate reliability.

RTG-Battery - The advantages, disadvantages, and other significant factors of this power source are summarized in Figure 5.1-11. The major factors influencing an RTG-Battery system selection for the SL electrical power source are mission duration, dollar cost, reliability, and weight.

The RTG-Battery system reduces the RTG requirement by a factor of two by utilizing batteries to supply the peak power demands of the SL electrical equipment. This results in a significant dollar cost reduction and a significant heat rejection reduction over an all RTG system. The penalty is an increased electrical system complexity with a corresponding reliability reduction, and the system

RTG SYSTEM BLOCK DIAGRAM



RTG - BATTERY POWER SOURCE CHARACTERISTICS

ADVANTAGES	DISADVANTAGES	OTHER FACTORS
Very long mission life	Expensive system and fuel	Ag-Zn batteries reduce
Energy output independent	Limited fuel availability	system weight
of weight	Continuous high thermal output	Acceptable volume
In transit energy source	Neutron and gamma radiation	
	Very complex electrical system	Good voltage regulation
Heat source	Life limited by battery cycle life	by use of regulators
Non-magnetic	Heaviest system with Ag-Cd batteries	
Power output fixed by battery design	Requires RTG and battery development	

limitations of battery cyclic capability.

The battery is sized to handle the peak power of communication periods at a 50% depth of discharge. Silver-cadmium batteries have been sterilized, and after the first few charge-discharge cycles of reduced capacity, have shown recovery to nearly 100% pre-sterilization capacity. Inadequate data is available on cycle life of sterilizable Ag-Cd batteries; however, cycle life of unsterilizable Ag-Cd batteries have been demonstrated beyond 500 cycles at 50% depth of discharge. No additional degradation beyond the initial first few cycles is anticipated for sterilizable Ag-Cd batteries. Therefore a Ag-Cd battery is assumed for the RTG-Battery system.

The RTG-Battery system for the SL electrical power requirements requires a 150 pound Ag-Cd battery if discharged to 50% capacity. This battery weight, plus the weight of the electrical system components associated with the battery, yield a total system weight in excess of the all RTG system. However, current Ag-Zn battery development using inorganic separators has demonstrated the feasibility of 2500 charge-discharge cycles at 25% depth of discharge. This separator has also proven sterilizable. Should further developments produce a sterilizable, high cycle life, long wet life Ag-Zn battery, the RTG and Battery system may be significantly lighter than an all RTG system.

A typical RTG-Battery power source electrical block diagram is shown in Figure 5.1-12. This system is considerably more complex than an all RTG system. For this reason, block redundancy is shown for the electronic equipment, and functional redundancy is shown in packaging the battery. The weight of the system takes into account these redundancy measures.

5.1.2.2 <u>Evaluation of Power Sources</u> - The comparison of the power sources is summarized in Figure 5.1-13.

Weight - Figure 5.1-14 shows the weight comparison for the electrical energy requirement. Figure 5.1-15 shows the weight comparison for the thermal energy requirement. The deciding factor for the weight of the Battery and Fuel Cell power sources is the thermal energy requirement. The Battery power source weighs 244 pounds to produce 9.3 kWh(t) with an associated electrical capacity of 8.1 kWh(e). The Fuel Cell power source weighs 122 pounds to produce 9.3 kWh(t) with an associated electrical capacity of 5.5 kWh(e). An equal weight Fuel Cell power source produces 22.5 kWh(e) and 37.5 kWh(t). The weight of the RTG and RTG-Battery power sources is determined by the 300 watt electrical power requirement and

RTG-BATTERY SYSTEM BLOCK DIAGRAM

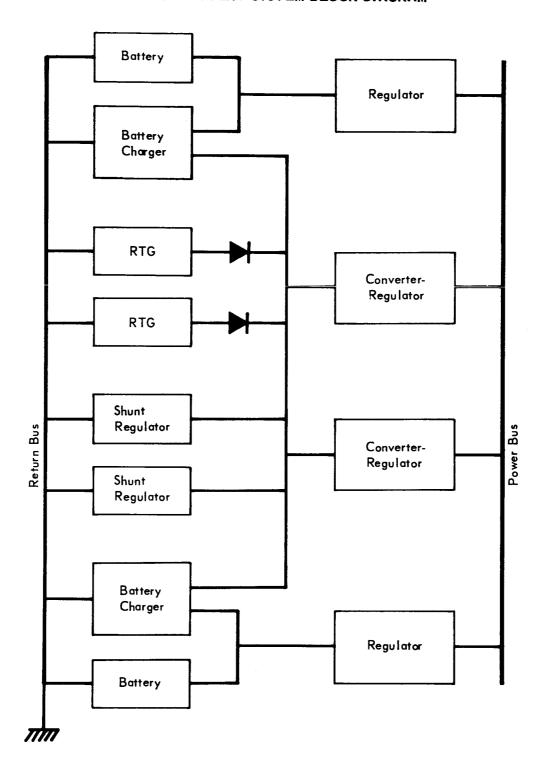
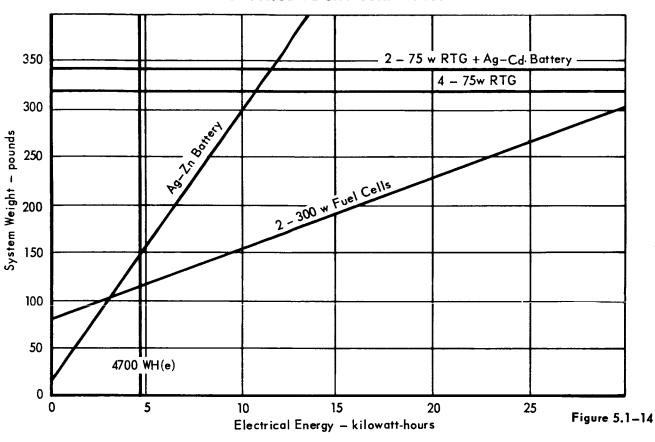
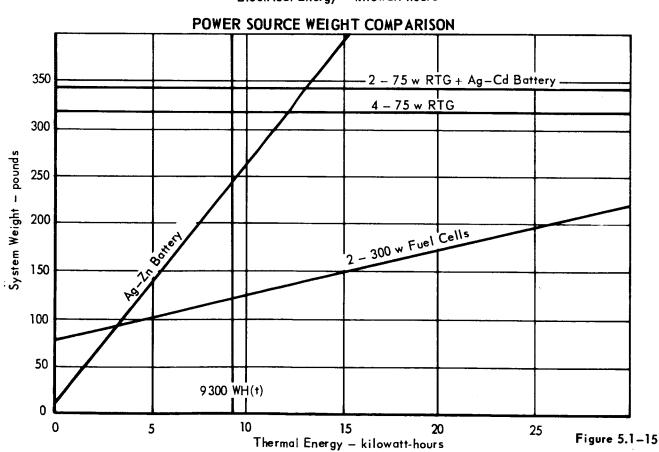


Figure 5.1-12

CHARACTERISTIC		BEST SYSTEM				
CHARACTERISTIC			RTG	RTG-BATTERY	DESI SISIEM	
Weight	122 pounds	244 pounds	321 pounds	342 pounds	Fuel Cell	
Volume	7,600 cubic inches	3,650 cubic inches	16,700 cubic inches	12,300 cubic inches	Battery	
Dollar Cost	\$400,000	\$20,000	\$28,000,000	\$14,000,000	Battery	
Available Electrical Energy	5500 watt-hours	8120 watt-hours	Unlimited	Unlimited	RTG or RTG- Battery	
Available Thermal Energy	9300 watt-hours	9300 watt-hours	Unlimited	Unlimited	RTG or RTG- Battery	
Peak Power Capability	600W Electrical 1000W Thermal	6600W Electrical 9900W Thermal	300W Electrical 6000W Thermal	2000W Electrical 6000W Thermal	Battery	
Environment Contamination	H2, O2, H2O purge gases	None for sealed battery	Thermal, neutron, gamma radiation	Thermal, neutron, gamma radiation	Battery	
Capacity Loss	Negligible plumbing loss; no tankage loss.	4—12% per month wet stand; negligible on float charge.	½% per year	½% per year	Fuel Cell	
Life	l-year stand feasible; 40-days opera- tion feasible.	10-month wet stand demonstration; 12 charge-discharge cycles demonstrated.	38-month design life	Limited by battery cycle life	RTG	
Availability	Development required.	Development required.	Development required	Development required		
Reliability	.9999	.9895	.9981	.9927	Fuel Cell	
Sterilization	Unknown	Feasibility demonstrated.	Inherent in design	Inherent in RTG design; battery feasibility demonstrated	RTG	
Operating Temperature	190°F to 220°F; 250°F limited performance.	50°F to 120°F; 20°F to 50°F limited output.	1050°F hot junction 525°F cold junction	1050°F hot junction 525°F cold junction 20°F to 100°F for battery	Battery	
Components	2 - 300-watt fuel cell stack 2 - hydrogen tank 2 - oxygen tank 2 - high pressure regulator 1-water storage tank plumbing	4 – battery (2030 watt-hour) 4 – battery charger	4 75-watt RTG 2 shunt regulator 2 converter- regulator	2 – 75-watt RTG 2 – shunt regulator 2 – converter- regulator 2 – battery 2 – battery charger 2 – regulator	Battery	

POWER SOURCE WEIGHT COMPARISON





5.1-21

is independent of energy requirements.

<u>Volume</u> - Figure 5.1-16 shows the volume comparison for the thermal energy requirement. The volume of the RTG and RTG-Battery power source is determined by the 300 watt electrical power requirement and is independent of any energy requirement. The RTG volume is computed as that of a cylinder of the overall diameter of the cooling fins. It should be noted that additional volume is required to insulate any temperature sensitive equipment located adjacent to an RTG.

Fuel Cells require gaseous reactant storage, and consequently the volume increases significantly with energy requirements. The volume is computed as that of a cube occupied by the 3000 psi spherical tank. This accounts for the fact that the space in the corner of such cube is not utilized in reality, except for tank mounting.

Battery volume is computed based on an electrical energy density of 2.4 watt-hours (electrical) per cubic inch. This density converts to 2.7 watt-hours (thermal) per cubic inch.

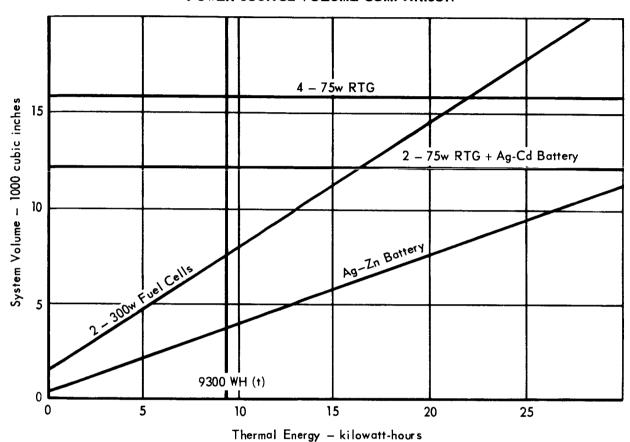
<u>Dollar Cost</u> - The dollar cost is that for each Surface Laboratory and does not include non-recurring engineering, development, and qualification costs. The RTG-Battery power source reduces the RTG unit cost over the all RTG system. However, an offsetting cost is the twofold development and qualification costs of the RTG and Battery.

Available Energy - The RTG and RTG-Battery power sources are not limited by energy requirements within the mission times envisioned for VOYAGER due to the use of a constant output, long life fuel. Fuel cell and battery power sources utilize a chemical-electrical conversion. Hence, their weight depends upon energy requirements, and a fixed weight system produces a limited quantity of energy.

<u>Power Capability</u> - The RTG is limited by its design to a specific constant power output. The Fuel Cell is limited by cell stack design to a maximum power level with minimum overload capability. The power output of a battery power source is limited due to internal resistance, which is very low for Ag-Zn cells, resulting in large peak power capability.

Environment Contamination - Fuel cells require periodic purging which expells oxygen, hydrogen, and a small amount of water vapor. Unless contained, these gases, especially the water vapor, may contaminate the local environment for various atmosphere composition experiments. An RTG produces continuous neutron and gamma radiation and is a concentrated source of radiant heat. These factors may be detrimental to sensitive experiments and may affect the local Martian

POWER SOURCE VOLUME COMPARISON



surface. Sealed batteries are considered passive devices producing no contamination and insufficient heat to affect the Martian surface.

<u>Capacity Loss</u> - Properly designed gas storage tanks exhibit no leakage, and plumbing leakage is negligible for the operating periods suitable for fuel cell consideration. RTG energy loss at 1/2% per year does not represent a significant energy loss factor even for long duration missions. Battery capacity losses on wet stand are very significant, but may be overcome by continuous float charging.

<u>Life</u> - Fuel cells have been assembled over one year prior to actual use and therefore show possibility of long stand time. Bench tests in excess of 40 days of operation demonstrate operating life an order of magnitude longer than required for the baseline mission time including extension. RTG design life has been shown feasible by the results of SNAP-27 operation.

To date, only two silver-zinc batteries have shown successful sterilization followed by 10 month wet stand time and at least one discharge cycle. One of these batteries has shown 11 additional charge-discharge cycles. Presently, no data exists for the cycle life of sterilizable Ag-Cd batteries.

Sterilization and Availability - All candidate power sources require significant development. Battery and Fuel Cell sources require sterilization development. Fuel cell manufacturers anticipate no significant cell stack changes to meet sterilization requirements. Fuel cells also require purge gas reduction and/or containment development. The RTG is inherently sterilizable but requires an extensive program to uprate and integrate the SNAP-27 basic generator design to VOYAGER requirements.

Operating Temperatures - The RTG operates at a hot junction temperature of $1050\,^{\circ}$ F, and the cooling fin base temperature is 480 to $500\,^{\circ}$ F for operation on Mars. Due to the high, continuous, heat generation, any equipment located in proximity of an RTG probably requires thermal shielding. The same is true, but to a lesser extent, of a fuel cell stack. Battery operating temperatures are compatible with other electrical equipment, but a battery may require thermal shielding from an adjacent high temperature heat source.

<u>Components and Reliability</u> - The fuel cell system presumes block redundancy of the fuel cell modules, and functional redundancy of the reactant system. This arrangement yields a very high probability of success based on failure rates experienced during the Gemini program.

The RTG system presumes functional redundancy of the RTG unit, and block redundancy of the electronic equipment. Assuming a .9999 probability of success

for each RTG unit, the RTG system probability is excellent. Addition of the battery components in a functional redundant mode for the RTG-Battery system, yields a lower probability than the all RTG system.

The Battery system has functional redundancy of the batteries and no redundancy of the battery charges. With the battery capacity of 8.1 kWh(e), the probability of completing the baseline, 4.7 kWh(e) mission is adequate but lower than the other systems.

5.1.2.3 Preferred Concept - The battery system is the preferred power source for the 1973 VOYAGER mission. It offers the cheapest, contaminant free, sterilizable approach, and of the proven sterilizable candidates, it is the lightest and requires minimum integration problems. Sterilization is considered proven feasible from current programs, and minimum development is required. Solar cells are undesirable because of the large array area and auxiliary power source required. The large area is not compatible with the spacecraft size and design wind constraint. Solar cell performance is questionable in a dusty, cloudy Martian environment, and therefore a solar cell system requires an auxiliary power source to meet these constraints.

The fuel cell is an attractive power source due to its light weight and excellent reliability with acceptable performance in other areas except sterilization and contamination. The sterilization ability is unknown, and the purge requirement produces environment contamination. Therefore, the fuel cell power source is not acceptable. However, if the sterilization and contamination factors can be overcome, the fuel cell is an attractive power source for moderate duration missions.

The RTG power source is very expensive, is heavy, and requires considerable integration problems not only in VOYAGER design, but with other programs and agencies involved with radioisotope fuel. The advantageous feature is long life for the initial fixed weight. Therefore, while it is an attractive alternative for later, long term missions, the RTG system is not appropriate for the 1973 VOYAGER mission.

The RTG-Battery system has the disadvantages of both the RTG and Battery power sources. The interesting feature is halving the RTG cost, but offsetting this is the twofold development and qualification requirements. Should silver-zinc batteries of long cycle life be developed, this system may offer a significant weight advantage over the all RTG system. Assuming sterilizable, long cycle life, silver-zinc batteries are not available, the RTG-Battery system is not as desirable

as an all RTG system

5.1.3 Battery Charging Study - Selection of the preferred approach to battery storage during the cruise phase of the mission requires additional wet stand testing on silver-zinc cells. Eagle Picher cells assembled into two, 6-cell batteries and tested by the General Electric Company, were sterilized and subjected to a 10 month wet stand period. The battery stored in a discharged condition yielded 98% of its initial capacity after the wet stand period, and has survived 11 additional cycles to date. The other battery stored in a charged condition, after replacing the wet stand capacity loss, delivered 75% of its initial capacity but failed to accept a charge after the second discharge. Analysis of the cells indicate that failure was due to dehydration of the electrolyte caused by loss of hermetic seal. Increased electrolyte concentration is believed to have resulted in accelerated oxidation of the separators. These tests indicate that a battery of this construction, on long wet stand in a discharged condition, has a high probability of survival. These tests, however, do not allow comparison with performance after extended wet stand in the charged open circuit condition or after extended wet stand with continuous charging.

Maintaining the batteries on continuous charge during cruise is selected as the preferred approach because:

- a. It is a lighter weight approach than open circuit charged stand since the battery need not be oversized to allow wet stand capacity losses;
- b. It is preferred over stand in a discharged condition since the battery is independent of the battery charger in so far as partial mission success is concerned with a maximum expected capacity loss of about 30% during cruise for a charger failure at launch;
- c. Internal power must be provided to the cruise commutator and instrumentation subsystems during periods when flight spacecraft power is not available; and
- d. The power dissipated in the battery chargers as heat, serves the same purpose as electrical heaters.

Three methods are available to charge batteries: constant current, constant potential, and float charge.

A constant current charger, as its name implies, provides a constant current flow into the battery, usually at a C/10 (battery capacity in ampere-hours/desired charge time in hours) or lower rate, with a consequent rise in charger output potential as the battery becomes fully charged. If charging is allowed to

continue indefinitely, overcharging and very high charger output potential results in gas production in the cells and, finally, cell rupture. Voltage limiting at $1.94 \pm .01$ volts per cell for silver-zinc cells is required to provide adequate charging potential and prevent overcharging.

A constant potential charger, as its name implies, provides a constant output potential at $1.94 \pm .01$ volts per cell with a consequent fall in output current as the battery becomes charge. However, for a deeply discharged battery, initial current flow will be excessive. Therefore, this charger usually employs current limiting to prevent high initial currents. If the current limit is set low, essentially constant current charging occurs for the majority of the charging cycle.

Continuous charging prevents silver migration, hence loss of silver from the positive plate thereby maintaining battery capacity. Continued charging, with either of the above methods, results in long term operation at 1.94 volts per cell. The minute flow of current at this potential will tend to oxidize all of the free silver in the positive electrode that is normally available for the conduction of current through the electrode.

A float charger, as defined herein, is essentially a current limited, constant potential charger at 1.98 volts per cell, with a second mode of constant potential output. When the current level, during constant potential charging, reduces to half the current limiting value, approximately C/100 rate, a current sensor transfers the battery output potential to the battery open circuit potential of 1.87 ± .01 volts per cell. This reduced potential prevents excessive silver conversion in the positive electrode and reduces the zinc dendrite growth over the 1.98 potential. The float charging method has shown promising results at the Goddard Space Flight Center. Although test data is limited, this method is selected for the VOYAGER program over the constant current or constant potential battery charging methods.

5.1.4 <u>Power Conditioning Study</u> - Based on the selection of a battery power source, the preferred method is a direct current power distribution system at unregulated battery potential utilizing decentralized power conditiong. This method provides maximum flexibility, freedom from catastrophic failure modes, and inherent electromagnetic compatibility.

Three methods of power conditioning were considered: distributing subsystem power requirements from a centralized power conditioner, distributing direct current at unregulated battery potential with decentralized regulation and power

conversion, and distributing alternating current at regulated potential from a centralized inverter to decentralized transformer-rectifier-regulators. A comparison of the methods is summarized in Figure 5.1-17.

Centralized power conditioning is not a desirable method due to existence of the catastrophic failure mode requiring redundancy, the use of isolation devices to prevent subsystem interactions, the inflexibility after the central power conditioner is designed, and the increased wire weight for multiple voltage distribution. The only apparent advantage is a weight saving by combining many subsystem power conditioning units into a common unit. However, this produces a catastrophic failure mode requiring block redundancy. Also, interaction of subsystems utilizing common voltages may require isolation from the common power source. Based on a preliminary evaluation, these redundancy and isolation requirements nullify any weight saved by utilizing a common power conditioner. In addition, this centralized method requires considerable integration to preclude subsystem designs from including superflouous power conditioning and to acquire early, accurate definitions of all subsystem power requirements. Any deficiency of the early definitions, yields an inadequate or delayed power conditioner design due to the inflexibility of this method after completion of the hardware design.

The combined method utilizing a central inverter, alternating current distribution, and subsystem transformer-rectifier-regulators is not preferred due to the interference from the high voltage, alternating current distribution system. Short rise and fall times of square wave, alternating current power distribution creates a broad spectrum of interference which is difficult to remove from susceptible circuits. The high amplitude magnetic field in the vicinity of a power line is difficult to confine with shielding, and effective cancellation by utilizing twisted pair distribution lines will not exist where such pairs pass through connectors, and where power buses are employed. High frequency components of the square wave will induce interference into the "ground loops" formed by multiple grounds of RF coaxial cables and RF shielding and any conductors routed through a connector containing power lines.

The distribution regulation of 28 ± 5 volts for the decentralized method is not an undue fluctuation, and subsystems involving motors, actuators, solenoids, relays, or heaters require no power conditioning. A major portion of this regulation value is due to the shift from the silver peroxide (Ag0) to the silver oxide (Ag $_2$ 0) plateau voltages. The other major portion of this value is due to reduction in the plateau voltage as a function of the remaining battery energy. The smallest portion

COMPARISON OF POWER DISTRIBUTION METHODS

METHOD	ADVANTAGES	DISADVANTAGES
Decentralized (Direct Current, Unregulated Potential Distribution)	Flexibility for later changes. Simplest distribution system. No catastrophic failure modes. Minimum redundancy required. Distributed heating within equipment bay. Best method to supply motors, actuators, solenoids, relays, heaters. Inherent EMI suppression from subsystem power conditioners.	Regulation: ±5 volts. Large conductor size required to distribute high power. Control of subsystem design required for efficient power conversion.
Centralized (Distribution of Subsystem Required Power)	Lightweight if no redundancy or EMI isolation is used. Distribution regulation: 1%	Flexibility limited by capability of power conditioner. Catastrophic failure mode exists. Block redundancy required for power conditioner. Multiple conductors required for multipotential distribution. EMI suppression required. Heavy system with: block redundancy, EMI suppression, multiple potentials. Large conductor size required to maintain regulation. Large conductor size required for low voltage distribution. Localized heating requires added thermal control. Subsystem integration required to minimize distribution voltages.
Combined (Alternating Current, Regulated Potential Distribution)	Minimum integration required with subsystem equipment. Distributed heating within equipment bay. Distribution regulation: 1%	Flexibility limited by capability of central inverter. Catastrophic failure mode exists. Block redundancy required for central inverter. Alternating current distribution causes severe EMI problems. Motors, actuators, solenoids, relays, heaters require no power conditioning and supplied from raw battery power. Twisted, two conductor distribution required.

of this value is due to actual load fluctuations. With the load profile of Figure 5.1-1 for the cyclic temperature day, the battery terminal fluctuation due to load changes should not exceed 0.4 volts, and the distribution system loss variation should not exceed 0.6 volts. This yields an overall load regulation of 1.0 (±0.5) volt. Therefore, this regulation is not considered a significant disadvantage of this decentralized method and does not warrent consideration of a central regulator to distribute regulated potential thereby incurring the disadvantages of increased weight and added equipment.

The requirement of the decentralized method for integration with and control of subsystem power conditioning design to utilize the most efficient conversion method is not considered a significant disadvantage. Unregulated power distribution is not significant as the major fluctuation is not of a dynamic character but rather a slowly changing basic potential level. The conductor size is usually the minimum size wire suitable for physical handling for all subsystems except the high rate transmitter. The transmitter will be supplied unregulated potential, direct current for any power conversion method because of the required conversion to multiple, high voltage outputs (1000-2000 volts).

The decentralized power conditioning method utilizing unregulated potential, direct current distribution is the preferred approach due to its flexibility, inherent electromagnetic interference suppression, and freedom from catastrophic failure modes.

5.1.5 <u>Power Grounding Study</u> - Based upon the conclusions of trade studies of Volume II and Volume IV for the CB and ESP respectively, the SL electrical power subsystem provides the backup energy for the CB and ESP electrical power subsystems. This requires some type of interconnection of all three power subsystem returns as well as power buses, and is discussed herein. See Volume II (CB), Part B, Section 5.6.3, for a discussion of the Flight Spacecraft/Flight Capsule power interface.

One method of interconnection of the power subsystem is to employ a DC-to-DC converter between each power subsystem. By this method, each power subsystem is electrically isolated, and each power subsystem has a single point ground (SPG). However, a weight increase for the converters is incurred, an increase in energy loss from the SL batteries is incurred due to converter inefficiency when the backup system is utilized, and a command or signal crossing the interface must be transformer coupled due to the absence of a common return system, incurring a further weight increase. This added equipment reduces reliability.

A second method of interconnecting the power subsystems is direct power bus interconnection. This requires the corresponding direct power return interconnec-With the ESP, CB, and SL power returns interconnected, the problem becomes where to ground the return system: in the ESP; in the CB; or in the SL. The ESP may not be required on later missions. The ESP is, therefore, ruled out because a grounding change from a flight proven system to an unproven system is required at the later date. The CB is utilized on all missions and appears a common point. However, when the SL is a rover the SL power system would float when detached from the CB. Locating the SPG in the SL eliminates the above problems of ESP and CB locations, but incurs somewhat longer return paths for the ESP and CB. However, these may be relatively short for the 1973 configuration, and a short ground path is provided for the SL where the bulk of the sensitive equipment is located. For later missions, when the SL is a rover, the CB return system floats upon removal of the rover. However, by that time, the CB has performed its service and is no longer required.

A third method of interconnecting the power subsystems is to switch power, return, and ground connections as the interconnection of the power subsystems is required. By this method, each power subsystem is grounded, and the grounds and returns are switched when interconnections are required for backup. The switches required in the return system reduce the reliability. Switches are required in the various ground paths to maintain only one SPG upon interconnection of the power subsystems. More than one ground point in the return system produces multiple ground paths and ground loops and is incompatible with EMC requirements. Any switch in the ground path is required to carry both dry circuit noise current and power subsystem fault current. The two requirements are not compatible.

Once a contact has carried fault current, it cannot be expected to perform in the dry circuit realm. Since the power subsystem returns for the CB, ESP, and SL are not normally interconnected, transformer coupling of the commands and signals crossing the interface is required.

The preferred grounding scheme, for direct current power distribution, is direct power return interconnection with the SPG located in the SL. This is the minimum weight system, without any return or ground switching problems. This grounding scheme also provides a flight proven system for future missions wherein the ESP may be deleted and the SL becomes a rover.

5.1.6 <u>Conclusions and Recommendations</u> - The preferred approach to the Electrical Power Subsystem for the 1973 VOYAGER Surface Laboratory is a battery power source

utilizing sterilizable, sealed, manually activated, silver-zinc batteries with distribution to the SL subsystem of direct current at the unregulated battery potential. Each subsystem provides its own power conditioning, thereby providing flexibility and inherent electromagnetic compatibility. During cruise the batteries are float charged from Flight Spacecraft cruise power to maintain their capacity during wet stand.

Solar cell performance in the Martian environment is indeterminate due to the unknown wind, dust, and overcast conditions. To properly evaluate solar cell selection for later missions, the addition of small fixed arrays is recommended to define actual solar cell performance under these conditions. Should actual performance be significant, solar cells are an attractive approach to mission extension wherein low average power is required.

The weight advantage of a fuel cell system is significant for missions of moderate duration. Therefore, a program is recommended to demonstrate sterilization and to reduce the purge requirements such that the purged gases are containable or of negligible effect upon the Martian atmosphere. If this program is successful, the fuel cell system is an attractive power source for the 1973 VOYAGER mission.

Insufficient test data is currently available to determine the advantages and disadvantages of battery wet stand in the charged versus discharged condition. Therefore, a program is recommended to evaluate sterilized, silver-zinc battery performance as a function of the wet stand method, i.e. fully charged, on float charge, or fully discharged.

SECTION 5.1

REFERENCES

- 5.1-1 "Report of the Ad Hoc Committee on Radioisotopes for Space Power", UB NASA TMX 1212, 1966 (Secret)
- 5.1-2 "Voyager Capsule RTG Integration Studies Summary Report for Phase B", General Electric Company, Missile and Space Division Report, ANSO PIR 1371 dated 7 August 1967.

- 5.2 SEQUENCING AND TIMING The Surface Laboratory (SL) requires a subsystem which governs the on-board automatic control of sequencing and timing functions during the periods of surface operations. This subsystem, denoted the Sequencer Subsystem, includes two functional units:
 - a. Sequencer and Timer (S&T) furnishes timing references and automatic sequential control of supporting subsystems during the SL operational mission, and
 - b. In-flight Test Programmer furnishes timing and sequencing required for exercising the SL subsystems as required for checkout of landed mission readiness.

Since the in-flight test philosophy and the rationale and analysis of the Test Programmer are discussed in Section 4.4, only the Sequencer and Timer analysis and selection is presented.

- 5.2.1 Requirements and Constraints The requirements and constraints which have influenced the design of the S&T are those of mission, system and subsystem effects upon the S&T, as shown in Figure 5.2-1.
- 5.2.1.1 Primary Constraints The requirement that the SL be entirely on-board sequenced requres an SL device to control all landed functions from a stored memory sequence. This on-board sequencing controller must contain an alternate (electrically reprogrammable) memory using updates through the FSC command link. The sequential controller memory must also be compatible with updates after landing utilizing the SL command link inputs. Self-test capability is included in the SL S&T to minimize the time and electrical energy required to perform inflight checkout. The Science Data Subsystem (SDS) sequences and controls the science instruments, sample acquisition and processing equipments. The remainder of SL sequential functions are controlled by the S&T, including control of all SDS-supporting subsystems and providing the primary SDS time references. 5.2.1.2 Secondary Constraints - The size of the S&T memory is determined by the the maximum duration and resolution of time delays, the number of different timebased marks or functions required by the SDS-supporting subsystems and the allowance for redundancy and growth capability. A number of different discrete stimuli are needed by the SDS-supporting subsystems. The number of S&T outputs includes an allowance for redundancy and growth capability. The S&T size and weight limitations are similar to those thoughout the SL; however, the requirement for minimum power applies especially to the S&T and like equipment which are on continuously. Also, the S&T must endure the peak full-charge battery voltage

when first activated on the essentially unloaded bus, and the lower voltage primary poweriinput when the unregulated bus is depressed under full load. The S&T must operate in the temperature, vibration, etc. environments throughout the VOYAGER-mission (per Reference 5.2-1) within the constraints of the FC structure and thermal control subsystems. The S&T memory storage must be designed to withstand the high temperature, shock and electromagnetic radiation environments.

5.2.1.3 Operational Requirements - The S&T will supply the following classes

- 5.2.1.3 Operational Requirements The S&T will supply the following classes of outputs which the SL supporting subsystems require:
 - a. Discrete (bilevel or Pulse) switching time-based control of subsystem operation (ON/OFF, START/STOP or Mode Selection)
 - b. Data Word (Train of digital data pulses proportional information transferred to using subsystem from S&T, and,
 - c. Reference Frequency cyclic clock or synchronizing periodic reference signals for subsystem timing.

These requirements form the bases for the corresponding memory and output sizing constraints described above. The SL S&T interface diagram, shown in Figure 5.2-2, summarizes the SL subsystem constraints upon the S&T as follows:

a. Inputs

- o Primary Power 23 to 33 VDC
- o Sensors Start commands from SL sensors/subsystems
- o Command Link Real-time and/or non-real-time signals to provide Earth updates or backup commands

b. Outputs

o ON/OFF, START/STOP, Mode commands

To Antenna Control (7)

To Electrical Power (13)

To Science Data System (4)

To Telemetry (8)

o Digital Data - Fixed or timing data words

To Antenna Control (2)

To Science Data System (4)

To Telemetry (130, including memory readout)

o Reference Frequencies

To Antenna Control

To Science Data System

To Telemetry

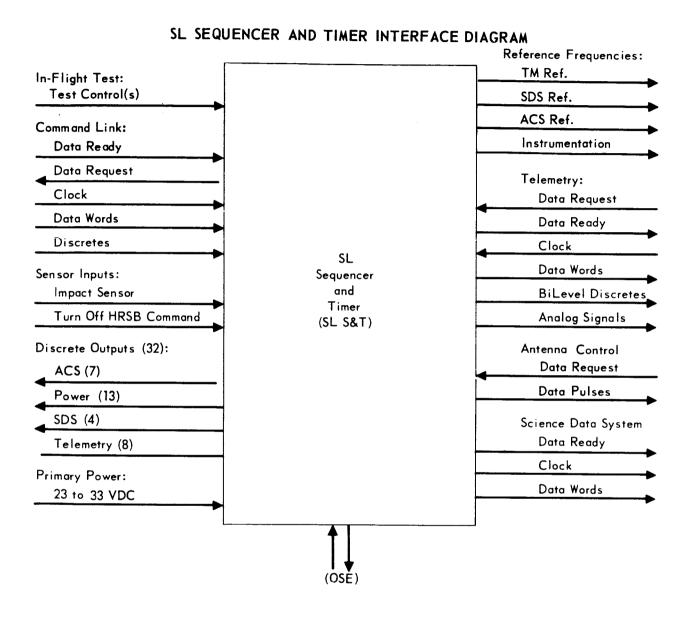
To Instrumentation

TABULATION OF SEQUENCER AND TIMER (S&T) DESIGN REQUIREMENTS AND CONSTRAINTS

REQUIREMENT OR CONSTRAINT	REASON
1. Stored memory sequence	SL must be entirely on-board sequenced
2. Memory alterable in flight (via FSC)	To enable post-launch mission modifications by Earth command (prior to de-orbit)
3. Me mory alterable after landing	To enable post-landing mission modifications by Earth command (following initial sequence of events)
4. Built-in-self-test	To verify proper operation after cruise-storage, in a shortest inflight checkout period
5. Size limitation of S&T packaging	Lander configuration requires minimum size electronics package
6. Weight limitation	Capability of launch vehicle for interplanetary mission requires lightest possible equipment
7. Input power constraints	Must consume minimum power to conserve battery weight, must operate with fluctuating voltage levels
8. Size of memory	Number of different time marks required to sequence SDS-supporting subsystems
9. Number of outputs	Number of different discrete stimuli required by SDS-support subsystems
 S&T provides sequencing and controls for SL subsystems supporting SDS 	SL sequences all post-landing functions; SDS controls its own science equipment
11. Withstand temperature, vibration, etc., environments	Voyager Mission subjects equipment to severe environment

Abbreviations: S&T: Sequencer & Timer

SL : Surface Laboratory SDS: Science Data System FSC: Flight Spacecraft



- 5.2.1.4 <u>S&T Functional Requirements</u> The resulting S&T functional definition is based upon the preceding requirements.
 - a. Accept, decode and store non-real-time (delayed) commands from the Command Decoder.
 - b. Based on these commands and an internally generated timing clock, time the delayed period from the corresponding "START" signal.
 - c. Activate the appropriate discrete output when this delay period has elapsed.
 - d. Upon request from a using subsystem, transfer the desired stored data word (command) to this subsystem.
 - e. Generate reference clock frequencies for use by interfacing subsystems.

Figure 5.2-3 shows the Functional Block Diagram of the SL S&T to accomplish these functions and the interconnections and inter-relationships of the functions themselves.

- 5.2.2 <u>Alternate Approaches and Selection</u> A study of the timing and memory techniques was performed to evaluate alternate implementation approaches.
- 5.2.2.1 <u>Timing Technique</u> The two methods which were considered to implement the "Count Down Time Delay" function in Figure 5.2-3 are the decrementing and incrementing timing techniques. In general, data words stored in the memory represent time-to-go-to-output following receipt of the appropriate sensor input signal. There are two ways of determing when to enable each output. The first way is decrementing (subtracting a pulse from) the stored word periodically after the sensor input is received and enabling the output when the word represents zero time-to-go. The second way is incrementing (adding a pulse to) a master time word, whose value is initially zero, periodically and comparing it to the stored word. When the words are equal, the output is enabled.

Operational Differences - In a destructive-read-out (DRO) memory, decrementing requires the stored word to be read from the memory periodically, decremented, and be written into the memory. The stored word is therefore changed at intervals equal to the time represented by its least significant bit. Incrementing requires the stored word to be read from the memory and then be restored in it without change. The read/write operation must be performed at intervals equal to the time represented by the least significant bit of the stored word. Therefore, the decrementing and incrementing methods are equal in the number of read/write operations required.

In this case, where time-data words with two different accuracies (and

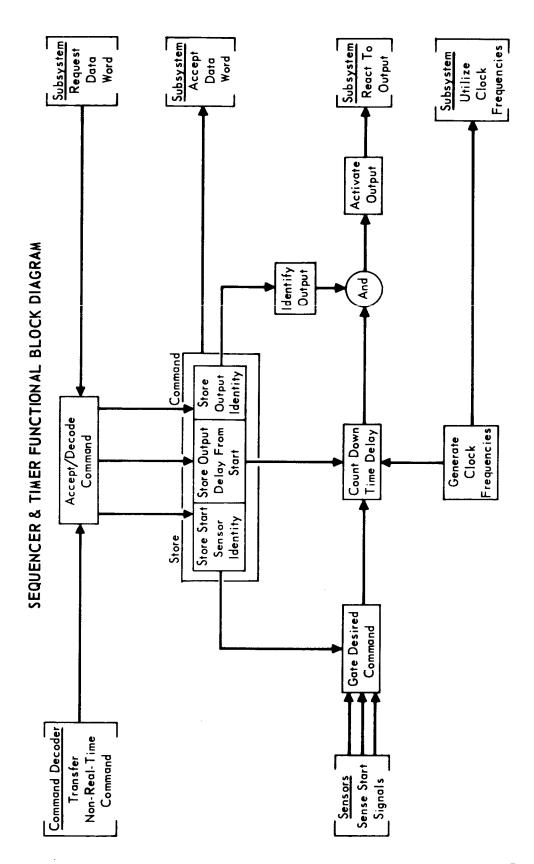


Figure 5.2-3

resolutions) are stored and counted, incrementing is more complex. Incrementing is complicated by the need for a master time word with the greater accurancy represented by its least significant bit (LSB) and for another master time word with the lesser accuracy represented by its least significant bit. Only by using binary coded decimal (BCD) coding for the stored words would one master word be required. However, BCD coding would require longer words and the resulting BCD incrementer would be more complex. Therefore two master words are required for the simpler of the two incrementing methods.

Since there are eight (8) sensor inputs which activate the same number of independent groups of time functions, either eight (8) sets of two master time words each are required, or one set of two master time words are required with the following method.

The one set of two master time words are incremented following receipt of the first sensor input. The stored words associated with the first sensor are periodically compared to the appropriate master time word. Upon receipt of the second sensor input, the stored words associated with it are modified by adding the existing master time to them and then comparing them to the master time words. The third through eighth groups of stored words are likewise modified upon receipt of their sensor inputs. Of course, all the master time words must be stored in the non-volatile memory to prevent their loss during power interruptions. The master time words are then similar to the stored words in the decrementing method since they must be read from the memory, incremented instead of decremented, and be written into the memory.

<u>Effect of Failure</u> - In the decrementing method, a malfunction during the read/write affects only one time function. In the incrementing method, a malfunction during the read/write of a master time word affects all the time functions associated with it.

Method Selection - The comparative characteristics of the preceding timing methods, summarized as follows, show the clear superiority of the decrementing over the incrementing method of timing applied to a destructive read-out non-volatile memory.

Characteristic	Decrementing	Incrementing	Incrementing
		(2 master time	(16 master time
		words)	words)
Read/write	All data words	2 master time words	16 master time words
operations	periodically	periodically and most	periodically
		of data words once	
Read only	None	All data words	All data words
operations		periodically	periodically
Read/write	One time	All time functions	All time functions
failure effect	function	associated with the	associated with the
		master time word	master time word
Complexity	Simplest	Most complex	Second most complex
Easiest to	Easiest	Most difficult	Second most difficult
implement			
Easiest to	Easiest	Second most	Most difficult
increase capacity	•	difficult	
Accuracy	Most accurate	Second most	Least accurate
	(Least opera-	accurate	(because of more
	tions per		operations per
	second)		second)

5.2.2.2 <u>Memory Technique</u> - The function "Store/Readout Command" on the SL S&T Functional Block Diagram Figure 5.2-3 involves the selection of the proper data storage or memory technique. The selection of memory techniques evolves directly into the corresponding choice of hardware devices for digital data storage. Since a detailed discussion of the tradeoff study of such storage devices is already included in the Telecommunication Selection of Data Storage Section 5.4.10, only a summary of the rationale as applied to the SL S&T is repeated here.

a. Functional Requirements

- o Capacity 3072 bits (128 words of 24 bits each)
- o Input from Command Link Serial data stream
- o Output to Telemetry Periodic Serial data stream at 500 to 800 bps
- o Output to Others Serial data stream at 10^4 to 10^5 bps

b. Technical Requirements

- o Maximum reliability
- o Minimize weight
- o Minimize size
- o Minimize volume
- o Meet environmental requirements including sterilization temperatures, shock and radiation

Candidate Memories - The requirement that the S&T retain the stored digital data words during the 30 week power off transit phase, and that these words be updateable by the command link before separation, necessitates a non-volatile memory with a capacity sufficient to store and manage the required data words. The volatile semi-conductor memory and the larger capacity dynamic magnetic memories are not considered for the SL S&T data storage.

The following types of non-volatile memories have been considered.

Magnetic Shift Registers - Magnetic Shift Registers (MSR) such as were used in the Gemini Electronic Timer offer wide temperature range, large operating margins, high noise immunity, low power, and high output voltage. Their disadvantages are speed (10 microseconds per shift) and size (120 cubic inches for 82 words of 16 bits). Each 16 bit MSR requires a shift current generator, transfer switch and write amplifier. The serial output allows simple serial arithmetic circuits.

Core Memory - Random access, coincident current, core memories, with a cycle time of 2 microseconds are available. A wide temperature range ferrite core stack can be used to eliminate the necessity for an oven to control stack temperature. The access circuitry of coincident current core memories is relatively simple and, when a matrix selection technique is used, the circuit component count can be kept low compared to other types of memories. Also in the random access mode, a word can be selected from the entire store in a fixed time (access time) which is independent of its location in the stack. The comparatively high output levels of core memories enable the use of sense amplifiers of relatively low gain-bandwidth product, thereby providing high reliability and high immunity to noise.

The standard core memory described above can be operated as a non-volatile memory by incorporation of a power shutdown sequencer.

The advantages of cores lie mainly in their ready availability, known

characteristics, and high degree of uniformity.

Non-Destructive Read Out (NDRO) Memories - Memories that fall into this category are thin film, drum, twistor, plated wire, and multi-aperture devices (MAD).

Magnetic drum or tape memories of the low bit densities required for the S&T would provide excellent NDRO storage but size, weight, and power requirements would be excessive. Disadvantages of drum and tape memories are the susceptabilities to both thermal and mechanical shock impulses and require a warm-up time after initial power turn-on. Another disadvantage is the access time which is of the order of milliseconds. Thin film, twistor and plated wire memories are presently in the stage of advanced development. They have a comparatively low output level and low signal-to-noise ratio and thereby require complex high gain-bandwidth amplifiers.

The multi-aperture device (MAD) memories have many of the characteristics of core memories previously discussed. Power requirements for a MAD memory are lower than core memories because consecutive interrogate cycles can be performed without the requirement to restore data, but access circuits would be more complex.

Memory Selection - Because of its advantages, the destructive read-out coincident current magnetic core memory has been selected as the S&T storage device. Again summarizing the results of the Data Storage Study of Section 5.4.10 as pertaining to a memory applicable to the SL S&T (about 3,000 bits) the following requirements were considered with the corresponding choices resulting.

- o Meets Functional Requirements magnetic core
- o Reliability magnetic core or semiconductor
- o Power magnetic core
- o Weight magnetic core or semiconductor
- o Volume magnetic core or semiconductor
- o Environment magnetic core
- o Cost magnetic core
- o Selected Approach magnetic core

An example SL S&T Memory Schematic Block Diagram is shown in Figure 5.2-4. This is the 3-D coincident current implementation of a magnetic core memory requiring the same total number of X and Y drivers as the sum of the core "dimensions" of the memory stack while the sense amplifiers and inhibit driver are each the same in number as the bit length of the data word.

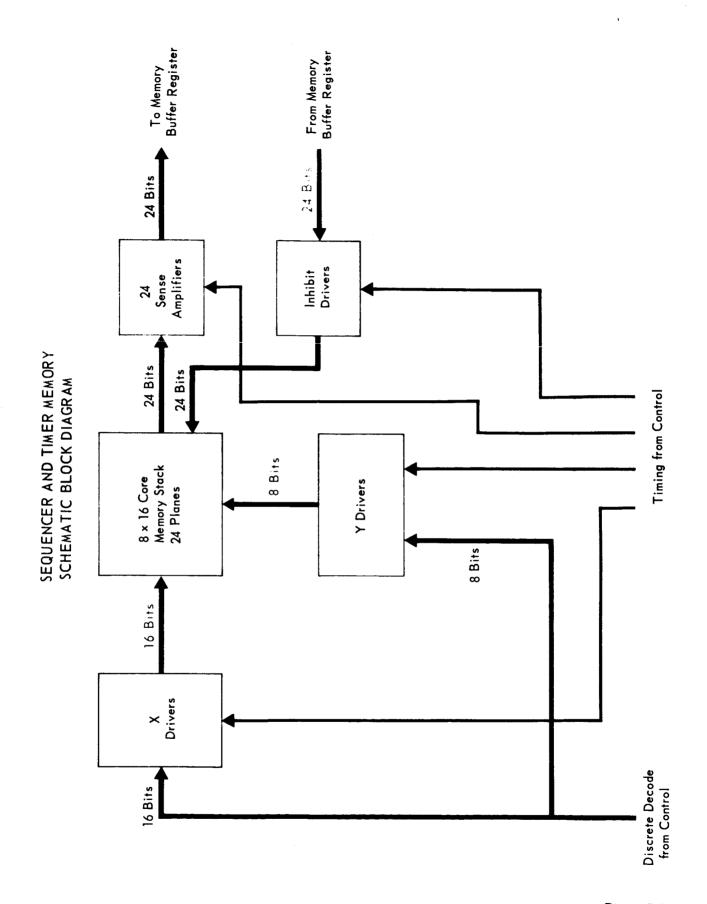


Figure 5.2-4 5.2-11

- 5.2.3 <u>Selected Approach</u> The alternates studied and the major factors involved in the selected techniques are summarized in Figure 5.2-5. The configuration of the SL S&T which complies with the preceding requirements and selections is as follows:
 - a. Coincident current magnetic core memory
 - b. Decrementing memory word timing technique
 - c. Memory Size 128 words, 24 bits each, reprogrammable in flight
 - d. Estimated Probability of 1973 Mission Success .9918
 - e. Size 288 in^3
 - f. Weight 11 pounds
 - g. Power Consumption 12 watts (23 to 33 VDC primary power)
 - h. Reference Frequency Outputs 1/240 Hz to 40 KHz, +.01% accuracy
 - i. Digital Word Outputs up to 16 bits/word at 500 to 40,000 pbs
 - j. Discrete Command Outputs 32 discretes, delayed in time up to 1 diurnal cycle from any of eight (8) selected input occurrences, ±2 to 0.5 sec. timing accuracy
- 5.2.3.1 <u>Design Points</u> The SL S&T design concept is based upon the selected implementation approaches to the subsystem requirements. The required outputs to SL subsystems are detailed as follows:

<u>Discrete Outputs</u> - The SL subsystems currently require 21 discrete commands subsequent to several possible mission "marks"; these discretes are desired at a time of up to one diurnal cycle after a given "mark" with a resolution of ±2 seconds. A more accurate time sequence is also required for delays up to 5 hours after the "mark" with resolution of ±0.5 second. These discrete output requirements are based upon the sequence of operational events for a typical 1973 mission, shown in Figure 5.2-6. The input stimuli and the required S&T reactions for this mission may be summarized as follows:

- o Power ON (S&T activation)
- o Update Memory (S&T verifies memory upon TM request)
- o Standby command (an "ARM" command to allow timing from a pre-separation mark to activate SL on internal power and to backup impact sensor SL initiation)
- o Touchdown (an "INITIATE" command resulting in 12 discrete outputs and the transfer of 2 digital data words)
- o Turn OFF HRSB Transmitter Command (a physical sensing indicating that HG Antenna is at its measured elevation lower limit inferring the HRSB

SEQUENCER AND TIMER (S & T) TRADE STUDY SUMMARY

S&T ELEMENT	ALTERNATE TECHNIQUES	MERITS OF SELECTED APPROACH
Memory Storage	Magnetic Core	Non-volatile memory
Techniqu e	Magnetic tape/drum	Less complex
	Semiconductor devices	More reliability, smaller, lighter and consumes less power
	Advanced static magnetic devices	Survives VOYAGER environment/ sterilization
		Lower development cost Better development status
Timing Technique	Decrementing Method	Sufficient speed and accuracy
	Incrementing Method	Less complex
	•	More reliable
		Easier design implementation
		Best increased capacity ability
		Greater flight experience

Selected Technique

SL SEQUENCER AND TIMER (S&T) SEQUENCE OF EVENTS

INTERFACE DESIGNATION	S&T INPUT (I)/OUTPUT (O)	SOURCE	S&T DESTINATION	BACKUP	MISSION TIME	S&T TIME
1-1	Apply Power to SL S&T	FS CC&S	SL Pwr (S&T)	MOS	T ₁₂ - 150 min	(Warmup)
1_2	Update SL S&T Parameters	MOS	SL S&T		T ₁₂ - 147 min	(Update)
0-1	Verify SL S&T Parameters	SL S&T	MOS	_	T ₁₂ - 117 min	(Verify)
1_3	Switch SL S&T to Standby	FS CC&S	SL S&T	MOS	T ₁₂ - 72 min	(Standby)
0-3-1	Switch SL to Internal Power	SL S&T	SL Pwr	MOS	T ₁₂ - 65 min	T _{es} + 7 min
1–4	Sense Touchdown	SL IS	SL S&T	CB IS	T ₂₆	To
0-4-1	Turn on SL Command Receiver (CR)	SL IS	SL CR (Pwr)	SL S&T	T ₂₆	+ 0 se c
0-4-2	Turn On SL Telemetry (TM)	SL IS	SL TM (Pwr)	SL S&T	T ₂₆	+ 0 sec
0-4-3	Select TM Day/Night Mode	SL S&T	SL TM	MOS*	T ₂₆	+ 0 sec
0-4-4	Turn on SL Science Data Subsystem (SDS) (B)	SL IS	SL SDS (Pwr)	SL S&T	T ₂₆	+ 0 sec
0-4-5	Turn on SL LRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS*	T ₂₆	+ 0 sec
0-4-6	Turn on SL Antenna Control Subsystem (ACS)	SL S&T	SL ACS (Pwr)	MOS*	T ₂₆	+ 0 sec
0-4-7	Start High-Gain (HG) Antenna Erection Sequence	SL S&T	SL ACS	MOS*	T ₂₆ + 30 sec	+ 30 sec
0-4-8	LRSB Transmitter Turn on Signal	SL S&T	SL TM	MOS*	T ₂₆ + 30 sec	+ 30 sec
0-4-9	Begin High-Gain Antenna Gyrocompassing (B)	SL ACS	SL ACS	SL S&T	T ₂₆ + 10 min	+ 10 min
0-4-10	End High-Gain Antenna Gyrocompassing (B)	SL ACS	SL ACS	SL S&T	T ₂₆ + 35 min	+ 35 min
0-4-11	Transfer Hour Angle Data Word	SL S&T	SL ACS	_	T ₂₆ + 35 min [†]	+ 35 min
0-4-12	Turn on SL HRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS	T ₂₇	T _o + 75 min
0-4-13	HRSB Transmitter Turn on Signal	SL S&T	SL TM	MOS	T ₂₇ + 30 sec	+ 30 sec
0-4-14	Transfer Time-to-Noon Data Word**	SL S&T	SL SDS	_		T _n - · · ·
0-4-15	Turn Off SL HRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS	T ₂₈ – 5 min	T _{es} – 5 min
	or		, ,		20	es
I_5	Turn Off SL HRSB Transmitter Command	SL ACS	SL S&T	_	(at EL Limit)	-
0-4-16	HRSB Transmitter Turn Off Signal	SL S&T	SL TM	MOS	T ₂₈ - 5 min	T _{es} - 5 min
0-4-17	Shutdown HG Antenna Tracking	SL S&T	SL ACS	MOS		T _{es} - 5 min
0-4-18	Transfer HA Reset Word	SL S&T	SL ACS	MOS	T ₂₈ – 4 min	– 4 min
0-4-19	Turn Off SL ACS	SL S&T	SL ACS (Pwr)	MOS	T ₂₈	T _{es}
0-4-20	Turn Off SL LRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS	T ₂₈	Tes
0-4-21	LRSB Transmitter Turn Off Signal	SL S&T	SL TM	MOS	T ₂₈	Tes
0-4-22	Transfer Time-to-Earthset**	SL S&T	SL SDS	-	-	T _{es} - · · ·
0-4-23	Switch TM to Night Mode	SL S&T	SL TM	MOS	т ₂₉	T _{ss}
0-4-24	Transfer Time-to-Sunset**	SL S&T	SL SDS	_	_	T _{ss} - ···
0-4-25	Transfer Time-to-Midnight**	SL S&T	SL SDS	-		T _m - · · ·
0-4-26	Transfer Time-to-Earthrise**	SL S&T	SL SDS	-	-	T _{er} - · · ·
O-4-27 (O-4-5)	Turn on LRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS*	т ₃₀	T _{er}
O-4-28 (O-4-6)	Turn on SL ACS	SL S&T	SL ACS (Pwr)	MOS	т ₃₀	T _{er}
O-4-29 (O-4-8)	LRSB Transmitter Turn on Signal	SL S&T	SL TM	MOS*	T ₃₀ + 30 sec	+ 30 sec
0-4-30	Begin Tracking Earth (HG Antenna)	SL S&T	SL ACS	MOS*	T ₃₀ + 1 min	+ 1 min
O-4-31 (O-4-12)	Turn on HRSB Transmitter	SL S&T	SL Radio (Pwr)	MOS	T ₃₀ + 75 min	+ 75 min
0-4-32	Transfer Time-to-Sunrise**	SL S&T	SLSDS	_	_	T _{sr} - · · ·
0-4-33 (0-4-13)	HRSB Transmitter Turn on Signal	SL S&T	SL TM	MOS	+ 75 min, 30 sec	+ 75 min, 30 sec
	Switch TM to Day Mode	SL S&T	SL TM	MOS	T ₃₁	T _{sr}

Sequence may repeat each diurnal cycle: (0-4-14 through 0-4-34)

Notes: ACS — Antenna Control Subsystem

EL — HG Antenna Elevation Angle

HG — High-Gain

HRSB — High Rate S-Band

LRSB — Low Rate S-Band

* — Non-real-time (delayed) backup by Earth command when possible

** — Time-to-XXX words to SDS once each minute after landing

B — Backup Signal

† — Requested by ACS at approximate time shown SL — Surface Laboratory

S&T - Sequencer & Timer

TM - Telemetry

IS - Impact Sensor

CR - Command Receiver

SDS - Science Data System

FSC - Flight Spacecraft
CC&S - Central Computer & Timer (FSC)

MOS — Mission Operations System
Pwr — Power (Electrical)

Predicted Times: T_{sr} — Time of Sunrise T_{er} — Time of Earthrise T_{m} — Time of Midnight T_{ss} — Time of Sunset T_{es} — Time of Earthset T_{n} — Time of Noon T_{o} — Time of Landing Mission Times: T_{12} — Separation (CB/FSC)

T₂₆ - Touchdown T₂₇ - Begin HRSB Transmission

 $T_{28} - T_{es}$ $T_{29} - T_{ss}$ $T_{30} - T_{er}$ $T_{31} - T_{sr}$

Transmitter shutdown)

Other S&T switching actions result from internally stored, pre-separation predicted time to Sun and Earth references (which may be updated after landing):

- a. Predicted Earthset (5 discretes results),
- b. Predicted Sunset (1 discrete results).
- c. Predicted Earthrise (7 discretes results), and
- d. Predicted Sunrise (1 discrete results).

<u>Digital Data Words</u> - The S&T must also supply 7 digital words for SL supporting subsystems for the 1973 mission previously described, with two more envisioned for extended missions.

- a. Antenna Control Subsystem (both words have <u>+</u>1 pulse resolution)
 Hour Angle (HA) word (up to 135 pulses)
 HA Reset word (up to 180 pulses)
- b. Science Data Subsystem (all words are required each minute with a ± 2 second resolution)

Time-from-landing (up to 1 diurnal cycle)

Time-to-Sunrise/Sunset (up to 1/2 diurnal cycle)

Time-to-Noon/Midnight (up to 1/2 diurnal cycle)

Time-to-Earthrise/Earthset (up to 1/2 diurnal cycle)

Days-from-landing (up to 750 days, ± 1 day, for extended missions)

c. Telemetry Subsystem - (required each minute)

Time-from-landing (up to 1 diurnal cycle +2 second resolution)

Days-from-landing (up to 750 days, ± 1 day, for extended missions)

<u>Reference Frequencies</u> - The SL subsystems in the preferred 1973 typical mission require 4 reference clock frequencies for internal counting or intersystem synchronization.

- a. Antenna Control Subsystem $1/240~\mathrm{Hz}~\pm.01\%$
 - 1.0 Hz +.01%
- b. Science Data Subsystem 1.0 Hz +.01%
 - 1.0 KHz + .01%
- c. Telemetry Subsystem 1.0 Hz +.01%
 - $1.0 \text{ KHz} \pm .01\%$
- d. Instrumentation Synchronization 38.4 KHz +.01%
- 5.2.3.2 <u>Functional Elements</u> The S&T conforming to this selected approach consists of the following functional elements, connected as shown on the schematic block diagram of Figure 5.2-7: memory, memory buffer register,

SL SEQUENCER AND TIMER SCHEMATIC BLOCK DIAGRAM

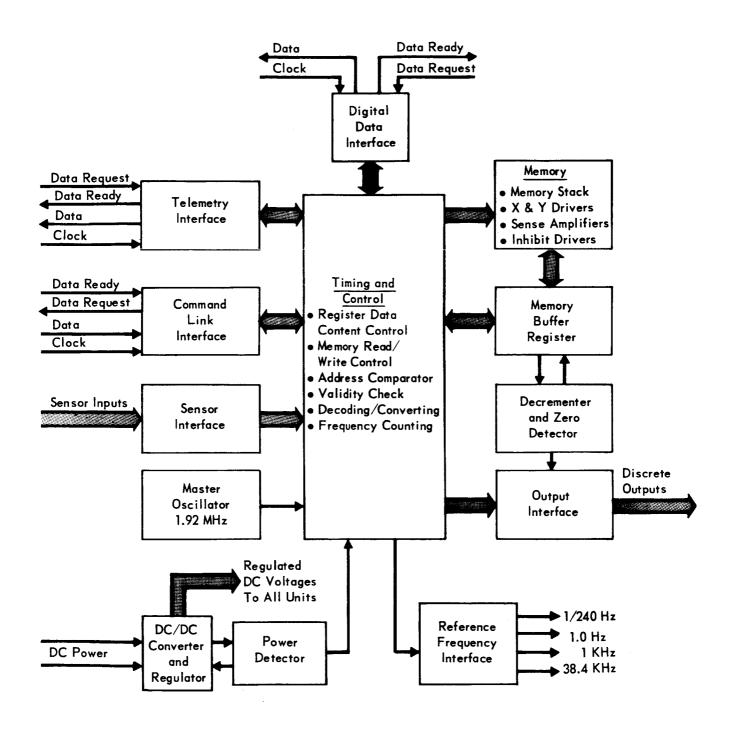


Figure 5.2-7

decrementer and zero detector, timing and control, master oscillator, converterregulator and power detector, and the required interface units (digital data,
telemetry, command link, input sensor, reference frequency and discrete output).
With these elements being standard or flight proven in design concept, the SL
S&T will perform the required functions within the constraining technical requirements analyzed herein.

List of References

5.2-1 1973 VOYAGER Flight Capsule Equipments Environmental Specification for Preliminary Design, McDonnell Report E191, revised 15 May 1967

- CONTROL SUBSYSTEM HIGH-GAIN ANTENNA The instrumentation and performance of the high-gain antenna control electronics is discussed in this section. The functional operation of the control electronics is developed in Section C3. 5.3.1 Summary - Studies have been performed to determine the suitability of inertial and radio control for erecting and pointing the high-gain antenna. The most effective means of orienting the antenna was found to be the use of a pre-programmed azimuth-elevation antenna, mounted on a polar or hour axis aligned to the Mars spin rate by a two-axis gyrocompass. Automatic radio tracking is incorporated
- as an Earth command option to provide a fine alignment capability. Calculations show that gyrocompassing in conjunction with knowledge of the local vertical, longitude and time of day can guarantee a pointing accuracy of 6 degrees which is the 3.6 db beamwidth of the antenna. On the other hand, the autotrack system can point the antenna to within one degree of Earth, which is less than the 0.2 db beamwidth of the antenna. The difference in performance (3.4 db) represents an improvement of 120 percent in bit handling capability.
- 5.3.2 <u>Technical Requirements</u> Two distinct capabilities are required, antenna and mount erection immediately after landing, and continuous tracking during the time the Earth is visible. Several requirements constrain the control system design to operate:
 - a. Without assistance from Earth.

5.3

- b. With 3 degree differences between actual and predicted landing site latitude and longitude.
- c. Within the latitude range of plus 10 to minus 40 degrees.
- With the Surface Laboratory tilted from the local vertical by as much as 34 degrees.
- e. Without dependence on the Sun.
- f. With an initial beam pointing error of less than 7.4 degrees.
- 5.3.3 Design Approaches The concepts that were studied are inertial and radio frequency tracking schemes, and a combination of both.
- 5.3.3.1 Single Axis Gyrocompass This concept employs a leveled turntable which carries an azimuth gyro. The gyro senses the tangential component of Mars rate at the landing site, and produces an error signal which torques the turntable in azimuth as long as the gyro senses any appreciable input. Azimuth motion will stop when the gyro input axis lies in the East-West direction. In this position, it is orthogonal to the spin axis of Mars and has no sensible input. The antenna

is attached to the turntable through azimuth and elevation gimbals. Since the turntable is now accurately oriented in both Mars surface coordinates and celestial coordinates, the two gimbals can be rotated through preprogrammed angles, and thus point the antenna beam toward Earth. In practice the turntable can be replaced by the azimuth gimbal since both rotate about the same axis. It must be emphasized that the success of this scheme depends on the availability of a well leveled base for the gyrocompass.

choosing some direction other than the local vertical for the azimuth elevation mount. A suitable direction is that of the Mars spin axis. Two gyrocompasses can be used to erect a spin axis mount. In the one gyrocompass concept azimuth rotations are measured with respect to the known direction, East. A similar angular index or reference must be provided for rotations about the spin or (more appropriately) hour axis of the two gyrocompass concept. The null position of either a pendulum or a Sun sensor attached to the outer gimbal of the hour axis is a suitable reference. Once the antenna is pointed at Earth, tracking can be accomplished by uniformly rotating the antenna and two outer gimbals about the hour axis. The four gimbals of the antenna pedestal are now arranged in the order: Laboratory - azimuth, elevation, hour axis, declination - antenna. It should be noted that the term azimuth has been reassigned from the antenna positioning gimbal (hour-axis) to the innermost axis as this axis most closely develops azimuth motion in the two-gyrocompass concept.

5.3.3.3 <u>Autotracking (Radio Tracking)</u> - RF scan and tracking information can be best employed in improving the accuracy of inertial aiming or for backup use in the event of malfunctions in the inertial command loop. In this case, the RF tracking equipment can be utilized to operate the antenna in either an elevation over azimuth or X-Y axis configuration in accordance with proven usage. This system consumes significant Surface Laboratory power and requires a constant signal (+130 dbm) from Earth as a target. To eliminate these requirements, it is desirable to limit the time spent in the autotracking mode, and this suggests a second reason for having RF tracking capability. While the system is tracking Earthmotion, the resulting declination movements can be recorded by Earth. At the conclusion of the day, changes in azimuth and elevation angles required for accurate hour axis alignment can be computed, and the pedestal gimbal angles can be readjusted. After the first day, enough data will have been taken to permit accurate clock tracking to continue indefinitely.

- 5.3.3.4 <u>Trade Study Summary</u> A summary of the major items evaluated during the control subsystem trade study is indicated in Figure 5.3-1. The preferred design is a two-axis gyrocompass erection mechanism for initial acquisition combined with an autotrack capability for fine alignment. A functional block diagram of this concept is presented in Figure 5.3-2.
- 5.3.4 <u>Performance Analyses</u> The performance of the control subsystem is defined in terms of the initial pointing error of the gyrocompass erection mechanism and by the subsequent tracking error. Error analyses of both capabilities have been completed.
- 5.3.4.1 Gyrocompass Beam Pointing Errors The 3 sigma errors considered in this analysis are:
 - o Gyro Drift

Fixed Torque	0.5 deg/hr
Mass Unbalance	1.0 deg/hr
Pendulum	1.0 deg
Landing Site Uncertainty	3.0 deg
Mars Polar Axis Uncertainty	1.0 deg
Lander Tilt From Vertical	0 to 40 deg
(Includes 6 degree allowance	
for crushable attenuator	
deformation.)	

The landing geometry for this analysis is shown in Figure 5.3-3. Point P denotes the landing point and the local vertical. Z' denotes the Mars polar axis and Z denotes the landing package vertical which forms the angle α with the polar axis. The angles τ , σ , and α locate the package vertical relative to the landing point, and the Mars polar axis. The angle τ represents the bearing from North of the plane containing the landing point and the package vertical, while the angle σ represents the angle between the local vertical and the package vertical, and accounts for terrain tilt. The gyrocompass alignment technique rotates the antenna through a two axis gimbal arrangement to align the antenna hour axis along the Mars polar axis. The antenna dish is then rotated through two additional gimbals in hour angle and declination so that it points toward Earth. Subsystem errors produce a beam pointing error that is conveniently described by components of declination error, and hour angle error. The declination pointing error as a function of landing point latitude is shown in Figure 5.3-4. The maximum error

CONTROL SUBSYSTEM TRADE SUMMARY CHART

SELECTION CRITERIA	GYROCOMPASS	AUTOTRACK	HYBRID (INERTIAL/RADIO)
Probability of Mission Success	Autonomous initial orientation in short time maximizes useful mission life. Gyrocompass is susceptible to wind induced vibrations	Initial acquisition is time consuming and may shorten useful mission life of the lander. Not as susceptible to vibrations as gyrocompass.	Functional redundancy provides better reliability than either radio or inertial techniques alone.
System Performance	Initial pointing error less than 5 degrees at site latitudes between plus or minus 10 degrees, and degrades with time after gyrocompass loops are turned off.	Tracking error is less than 1 degree, and is independent of latitude and time.	Final error is same as tracking error which is less than 1 deg, and is independent of latitude and time.
Development Risk	Gimbal bearings and drive motors must be qualified for sterilization.	Gimbal bearings and drive motors must be qualified for sterilization.	Use of both approaches incurs the dovelopment problems of each approach. Gimbal bearings and drive motors must be qualified for sterilization.
Versatility	Best performance is achieved at low Martian latitudes and with level lander base.	Search program can be adapted to landing site.	Most versatile. Gyrocompass assures quick acquisition, autotracking gives small tracking error. Either mode can fulfill all mission requirements independently.
Cost	Gyrocompass loop and gimbals require develop- ment funding.	Autotrack circuitry and gimbals require development funding.	Most expensive. Development of two techniques must be funded.

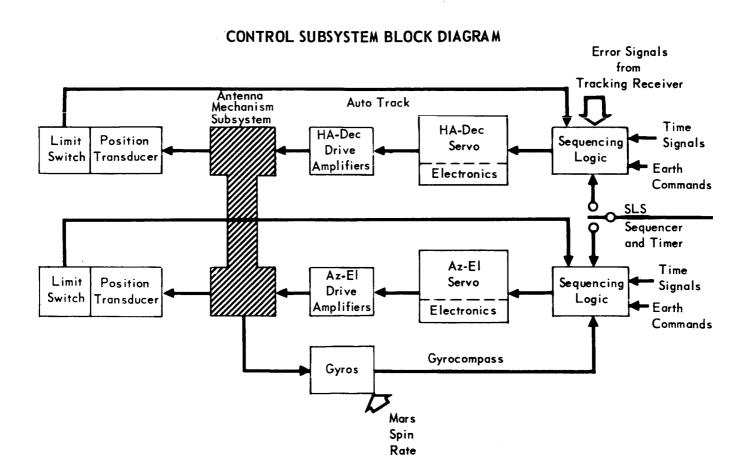
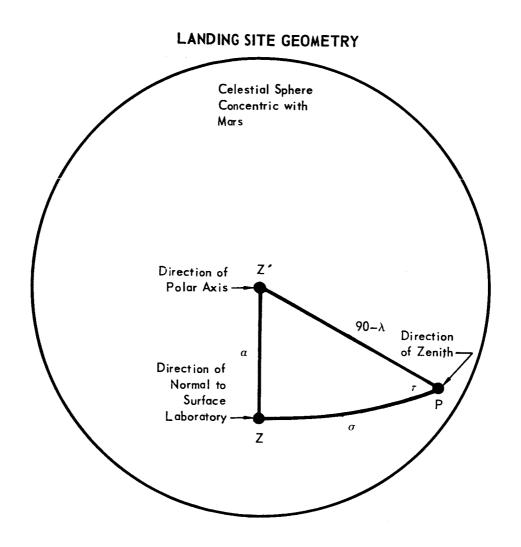
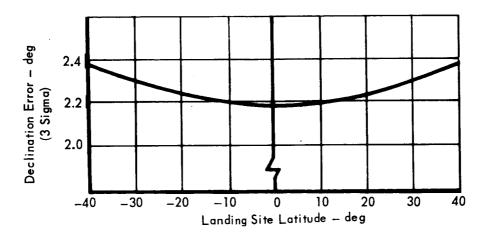


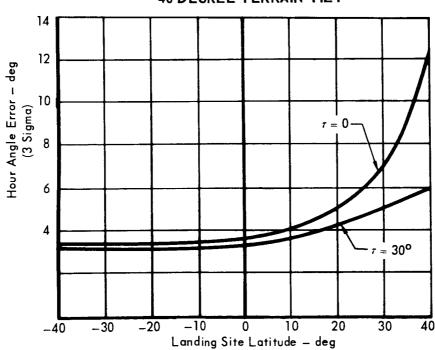
Figure 5.3-2



A. ANTENNA DECLINATION ERROR



B. ANTENNA HOUR ANGLE ERROR WITH 40 DEGREE TERRAIN TILT



is less than 2.4 degrees for all possible landing point latitudes. This error results from gyro drift and Mars polar axis uncertainty and is independent of the other error sources.

The hour angle pointing error is a function of all the error sources. Figure 5.3-4 shows the worst case errors which occur at a τ angle of zero and a 40 degree terrain tilt. An error of 12.3 degrees will occur at a landing site latitude of 40 degrees. The rapid increase of azimuth error with increasing latitude is a direct result of gyro drift. The errors corresponding to a τ angle of 30 degrees is shown for comparison as the lower curve of Figure 5.3-4.

Boundaries for hour angle error of 6.0 degrees or less are shown in Figure 5.3-5 with τ angle as a parameter. It is seen that for positive landing point latitudes, bearing angle magnitudes of 30 degrees or greater satisfy this condition for all possible values of terrain tilt and latitude. For negative landing point latitudes, τ angle magnitudes of 150 degrees or less satisfy this condition.

Hour angle errors for two other conditions are shown in Figure 5.3-6. If there is no terrain tilt, the maximum hour angle error is less than 3.8 degrees at all latitudes. This error increases as the tilt increases, and the specific case of 40 degrees of tilt is also shown on Figure 5.3-6 for τ angles of plus or minus 90 degrees.

5.3.4.2 <u>Autotrack Accuracy Calculations</u> - In monopulse tracking systems, there are generally four sources of tracking error. These are:

- o Receiver Thermal Noise
- Wind Gust Torques
- o Phase and Amplitude Unbalance
- Dynamic Lag

The contribution of each of these sources and the effect on overall system performance are discussed in this section.

Receiver Thermal Noise - The limitation placed on tracking accuracy due to thermal noise can be expressed as:

$$\sigma_n = 1/k \sqrt[n]{KT B / C_{Sum}}$$

Where:

 σ_n = The RMS Thermal Noise Error (degrees)

k = The Normalized Error Slope (volts/volt deg)

K = Boltzmann's Constant

T = Difference Channel Temperature (degrees Kelvin)

PERFORMANCE BOUNDARIES

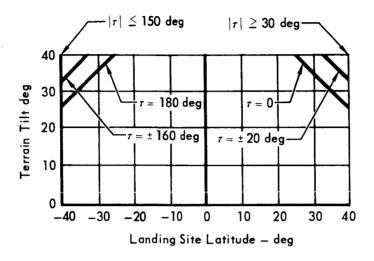
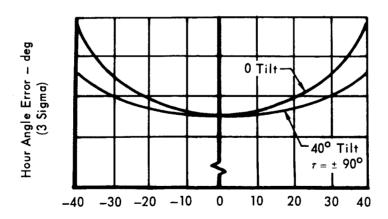


Figure 5.3-5

ANTENNA HOUR ANGLE ERRORS



Landing Site Latitude - deg

Figure 5.3-6

5.3-9

B = Equivalent Two-Sided Servo Position Loop Bandwidth (cps)

 C_{Sum} = Sum Channel Signal Level

The normalized error slope in the difference channels (k) is a function of antenna size, squint angle of the offset tracking beams, and losses between the feed and the tracking receiver input. The optimum k occurs for squint angles that are approximately one-half of the antenna 3 db beamwidth, and for this case is

$$k = 0.115 \text{ volts/volt-deg}$$

which is the value as referred to the comparator output. This value is further reduced by resistive and coupling losses in the feed line amounting to 8.5 db. The value of k referred to the tracking receiver input is

$$k = 0.115 \times 0.14 = 0.016 \text{ volts/volt deg}$$

The difference channel noise temperature includes contributions from atmospheric losses, feed loss, and receiver noise. However, coupling losses are nonresistive and do not influence the noise level, while atmospheric losses are negligible with respect to the receiver noise temperature and can be ignored (this assumes the antenna is not pointing at the Sun or other discrete galactic noise sources). With these assumptions established, the noise temperature in the difference channels is

$$T = 2938^{\circ}K$$

Position-loop noise bandwidth of the servo system is generally defined only when operating in the closed-loop autotracking mode, as they can be functions of various parameters within the system. For discrete sampling operation, the bandwidth is not clearly defined and will depend somewhat on the time constant of the servo low pass filter. In all cases, however, B will be less than 2 Hz and to be conservative, this value will be used to determine thermal noise error.

The sum channel signal strength can be computed if it is assumed that the DSIF will radiate 130 dbm of effective power.

$$C_{S_{11}m} = -114.4 \text{ dbm}$$

With all the unknowns established, the thermal contribution to tracking error can be computed:

$$\sigma_n = 0.3$$
 degree (RMS Thermal Noise Error)

<u>Wind Gusts</u> - The effect of wind gusts on continuous autotracking systems is a function of structural design and the response of the servo system to error inputs. For the proposed system, there is a relatively long time interval between position changes and the servo is not designed to respond to rapidly changing wind gusts.

Therefore, the total uncompensated wind gust effect will be considered the error for the purpose of evaluating tracking performance, and this is completely determined by mechanical design. The antenna and its pedestal will be designed so that for the worst case, the rms wind error will be less than 0.5 degrees.

<u>Phase and Amplitude Unbalance</u> - Tracking error from this source is expected to be insignificant in relation to the magnitude of errors from other sources.

Dynamic Lag - Dynamic lag, which results from a difference in time between the detection of an error signal and its correction by the servo, can be defined for this discrete system as the maximum error which has to be detected before the servo will pulse the drive motors. The minimum error threshold should exceed one half of the step interval. The step interval involves a trade-off between maximum permitted error and maximum allowed power consumption. The stepping interval has been chosen as 1 degree, and the antenna is stopped after an error of 0.8 degrees is detected. The maximum lag error will therefore be 0.8 degrees.

The root sum square value of the combined error sources is 1 degree.

- 5.4 TELECOMMUNICATIONS Mission success for the Surface Laboratory can be measured the the amount of pertinent scientific information received at the DSIF. The telecommunications subsystems must accommodate and transmit this information. Near real time data recovery and command authority are high valued considerations in this design. The ability to adapt to unexpected environments and take maximum advantage of fortuitous circumstances is mandatory. Meeting these requirements within the constraints of size, weight, and power has been the primary consideration in our studies.
- 5.4.1 <u>Telecommunications Design Approach</u> Our studies have been concentrated in three major areas: telemetry and data acquisition, command functions, and RF link design. A block diagram of the preferred approach is shown in Figure 5.4-1.

The telemetry and data acquisition studies considered the functions of both the telemetry subsystem and the Science Data Subsystem as a single entity (called the data handling system) in many of the studies. The preferred approach draws a distinct interface between these subsystems as discussed in Section 5.4.9 and summarized in Section 5.4.1.3.

The Mariner command technology was applied to the SLS command function, resulting in a straightforward design.

The RF link design, summarized in Section 5.4.8, evolved from and consideration of system level failure modes, data requirements, and current state-of-the-art technology. As shown in Figure 5.4.-1, we have selected a dual telemetry link approach which consists of a high-rate link and a low-rate link, both transmitting directly to Earth. The command link is also direct from Earth, and provides a metric tracking capability when used with the high-rate transmitter in a transponder mode.

The design approach is summarized in Figures 5.4-2 and 5.4-3. The TCM design is constrained by the data load and the mission time line. These are summarized in Figures 5.5.-4 and 5.4-5, respectively. The data collection and transmission modes derived from these studies are shown in Figure 5.4-6.

The post-landing data collection rates are either much greater than a conservatively designed link can manage in real time, or much less. The data storage subsystem design is based on this fact. As discussed in Section A3.3.4, all data transmitted on the high rate link are transmitted from storage on a "last in-first out" basis.

5.4.2-2

5.4-2-1

Figure 5.4-1

• 31 AUGUST 1967 F694 • VOLUME III • PART B REPORT

HIGH RATE LINK AND LOW RATE LINK TECHNICAL DESIGN APPROACH

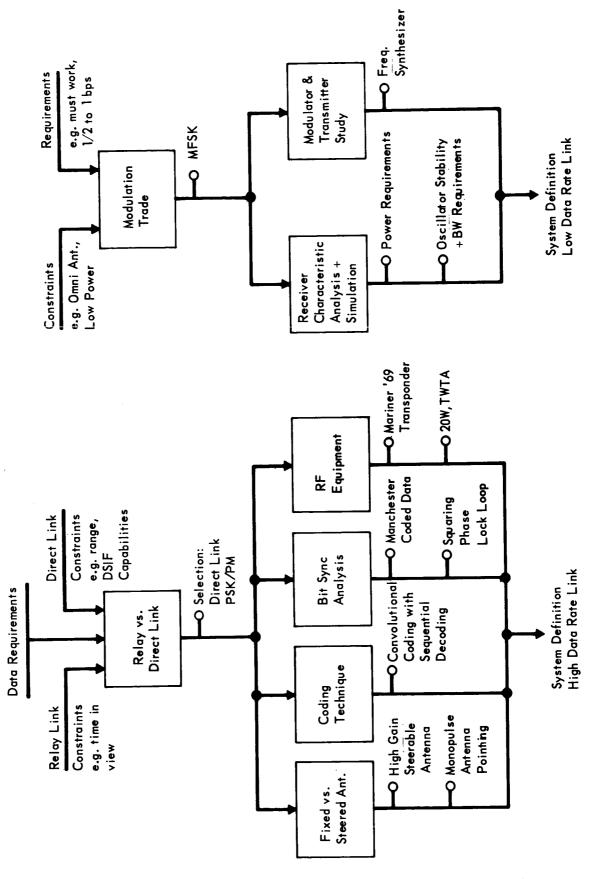


Figure 5.4-2

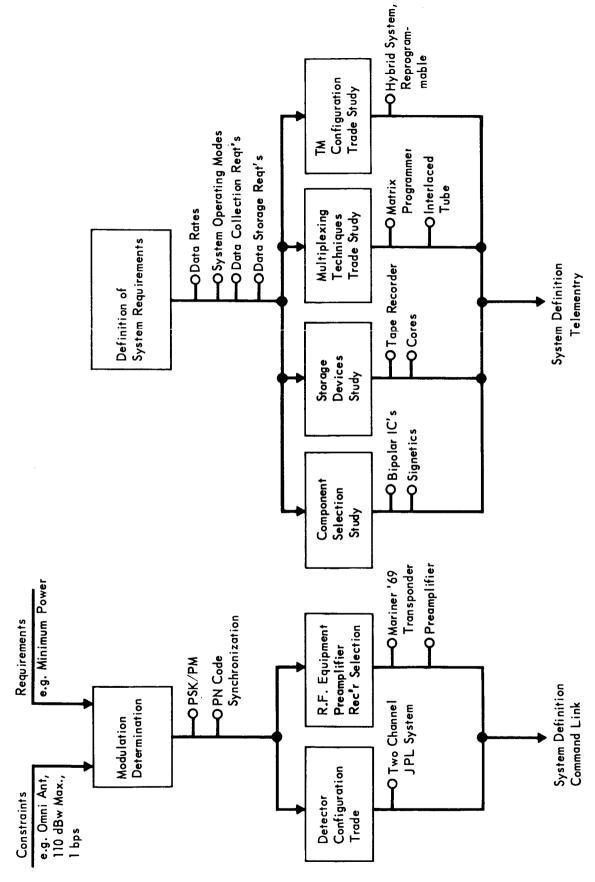


Figure 5.4-3 5.4-4

SURFACE LABORATORY INSTRUMENTATION LIST

			!				SAMPL	SAMPLES/SECOND		
PARAMETRIC NUMBER	PARAMETER	RANGE/ CHARACTERISTICS	TYPE	YOARUOOA	CKNISE LAUNCH &	CHECKONT PREPARATION	DE-ORBIT ENTRY	DAY	NIGHT	SUNRISE/
VS-1	Visual Imaging (Facsimile) A	2 Cameras Low Resolution D Secondaria	. 🗅	6 Bits				5 Lines/sec		
		Fan - Stero Mode - 9000 Bits/sec - 2.16 × 10 ⁶ Bits/Frame								
		medium Resolution - 12,000 Bits/sec - 0.96 x 106 Bits/Frame	د	o 5 5						
		Checkout - 1 Frame per Camera, Low Resolution 300 Elements x	۵	6 Bits		5 Lines/sec				
VS-2	Camera 2 Video	Same as Camera 1	۵	6 Bits		5 Lines/sec		5 Lines/sec		
VS-3	Camera No.		ᆈ	i		1/Frame		1/Frome		
VS-4 VS-5	Frame No. Azimuth	1/10 Line (L.R.) 1/50 Line (M.R.)	م د	3 Bits 7 Bits		-/ Frame		I/Frame		
VS-6	Field Stop		<u>8</u>			1/Frame		1/Frame		
VS-7	Lens 1 Position		교 교			1/Frame		1/Frame		
VS-9	Cam No.		ᆸ			1/Frame		1/Frame		
VS-10 VS-11	Motor 2 Temperature (2)	Engineering Status		7 Bits		1/15		1/900 1/900		
VS-12	Tube Temperature (2)	Engineering Status	<u>:</u>	7 Bits	.00	1/15	6.	1/900		
VS-13	Test Lamp Voltages (2)	Engineering Status	,			1/15		1/900		
VS-14	lest Lamp Current (2)	Engineering Status		/ Bits		SI /-		006/1		
2	Atmospheric Properties (2)		=			1/16		000/1	000/	9%
PS-2	Tessure		2 1	8 0 80 8 1 2 5 8 1 2 5		51/1		1/900	1/300	09/1
PS-3	Humidity		로			1/15		1/900	1/900	1/60
PS-4	H.W. Anemometer 1		크			1/15		1/900	1/900	1/60
PS-5	H.W. Anemometer 2		_ :			1/15		1/900	00/1	09/1
PS-7	H.W. Anemometer 3		1 1	8 0 E		1/15		1/900	206/1	09/1
PS-8	H.W Anemometer 5		L.	8 Bits		1/15		1/900	1/900	1/60
PS-9	Pressure Anemometer 1		۵			1/15		1/300	1/300	1/300
PS-10	Pressure Anemometer 2		Δ:			1/15		1/300	1/300	1/300
PS-11	Pressure Trans Temp	Engineering Status	_ :		8	1/15	<u>e</u>	1/900	1/900	1/900
PS-12	Anemometer lemperature	Engineering Status		7 Bits		1/15		1/3600	1/3600	1/3600
PS_14	Anemometer Temperature 3	Fragineering Status] _ 			51/1		1/3600	1/3600	1/3600
PS-15	Anemometer Voltage 1	Engineering Status	: -:			1/15		1/3600	0096/1	1/3600
PS-16	Anemometer Voltage 2	Engineering Status	7			1/15		1/3600	1/3600	1/3600

Figure 5.4-4

5.4-5-1

	45_1	Alpha Spectrum A	256 - 16 Bit Words/Sample	٥	8 Bits		1/Sample		:	·		
	\$ v	Proton Specifican		_			1/Sample					
	AS-2	Head Temperature	Engineering Status	_ 	7 Bits	.00	1/300	<u>e</u>	1/900			
	AS-4	Head Temperature 2	Engineering Status		7 Bits	100.	1/300	6.	1/900			
	AS5	Voltage	Engineering Status		7 Bits		1/300		1/900			
	A.S6	Voltage	Engineering Status	로	7 Bits		1/300		1/900			
	AS-7	Det Data Rates (6)	Engineering Status	土	7 Bits		1/300		6/hr		-	
	AS-8	Det States (6)	Engineering Status	В	7 Bits		1/300	·	6/hr		-	
		Gas Chromatograph 4								-		-
	Ŧ	•	For Atmos &	보	8 Bits	-			1.0			
	H-2			로	8 Bits				1.0			
	H-3		6400 Bits/ Used for Soil	로	8 Bits				1.0			
	H4	Column 3 Lo Sens	Analysis Analysis 38,400	土	8 Bits				1.0			
	H-5	Column 3 Hi Sens	DITS/Andlysis	로	8 Bits				1.0			
	9H	Column 3 Lo Sens	(sdub)	<u></u>	8 Bits				0.		-	
	H-7	Column 4 Hi Sens		로	8 Bits	-			1.0			_
	H-8	Column 4 Lo Sens		로	8 Bits				0.			
	H-9	Column 1 Temp		ቷ :	8 Bits		1,30		1/120			
	H_10	Column 2 Temp	During Chromatograph Use Only	<u>-</u>	8 Bits		1/30		1/120		-	
4	Ξ	Column 3 Temp			8 Bits		1/30		1/600			
5,	H-12	Column 4 Temp			8 Bits		1/30		1/600			
4-	H-13	Oven Temp		<u></u>			1/30		1/3000			
ح.	H-14	Carrier Gas Pressure	Engineering Status			8	1/30	<u>ė</u>	1/3600			
	H-15	Calib Gas Pressure	Engineering Status		8 Bits		1/30	<u>ë</u>	1/3600			
- 2		Metabolism 1 & 2 S										
<u>.</u>	GU-1			Δ	74 Bits		1/60		1/60	•		
	GU−2	Science Word II		Δ	30 Bits		1/60		1/60			
	, I	(In SITU)	Fraine Status		55 Bits		1/600		1/600			
	}	ife Detection (Growth)										
	L Z	Housekeeping	Fach line active for 100 sec	<u></u>	8 Bits		1/20		1/20			
	NT-2	Turbidity	sequentially, 5 parameters	보	8 Bits		1/20		1/20			
	ZT-3	- Ta	commutated on each line to be									
			sampled every 20 sec Engg Status									
		•	mux as housekeeping.									
		Surface Probe										
	- a	Temperature (10)		<u>ة</u> لـ	8 Bits		09/1		1/900	006/1	09/1	
	P -3	Pump Gas Pressure	Engineering Status	느	7 Bits	.00	1/900	9.	1/3600	1/3600	1/3600	
		Spectroradiometer /8 Part I										
	SR_1	Isolation		Ħ	30 Bits		72/72		1/900	1/900	1/900	

1/900						-																																	
006/1																																							
1/900	1/2 hr	1/2 hr	JU 7/1				1/60	1/60	1.0	1.0	1/2	1/4			1/60	1/60	1/60	1/3600		1/900	1/900	1/900	1/900	1/900	1/900	1/900	006/1	96/	006/.	006/1	006/1	1/900	1/900						
																		<u>.</u>																					_
72/72	72/72	2//27 57/25	7//7/	C .	c/1													1/700		1/30	1/30	1/30	1/30	1/30	1/30	1/30	02/1	06/1	05/1	1/30	1/30	1/30	1/30	1/30	1/30	1/30	1/30	1/30	
												•						8									·												-
30 Bits	6 Bits	2 Bits	2 0 12	2 0 1	sits /		7 Bits	7 Bits	7 Bits	7 Bits		7 Bits		7 Bits		-		_		3%	3%	3%	3%	3%	3%	3%	3%	% E	%6	3%	3%	3%	3%	3%	23 Bits	3%	3%	23 Bits	-
רר	로,	₹:	<u>.</u>	1 :	뒫		로	로	茾	占	뮵	土		爿	B	ם	В	Я		로	7	土			로	로	로 :	분 :	Į.		_	로	土	로	٥	로	로	۵	-
rtu	1728 Bits/2 hr	8 Bits/2 hr	2304 Bits/2 hr							During 2 hour operation only.		_					-			-90 to -150 dBm	-118 to -142 dBm	- 06 ∓	0-3 mw				0-5 ₩			25° to 150°F	25° to 150°F								_
Temperature Dart 2	Radiation Intens.	View Direction	Test 1 and Comment		lest Lamp Voltage	Soil Sampler 9	Azimuth	Reach	Voltages (2)	Currents (2)	Direction	Foot Position	Sampler Processor	Density	Rock Crush Status	Purge Status	Bin Ready (3)	Gas Supply Pressure	Radio Subsystem	Receiver AGC (Coarse)	Receiver AGC (Fine)	Receiver Static Phase Error	Receiver L.O. Driver	TWTA Temp (2)	TWTA Cathode Current	TWTA Helix Current (2)	Low Gain Power Drive	Low Kate Transmitter Power	High Kate Transmitter Power	Low Rate Transmittal Temp	High Rate Transmittal Temp	Low Rate Oscillator Driver	High Rate Oscillator Driver (2)	Receiver Input SNR	Low Rate Transmitter Freq	Modulator Verification	Receiver Input Power	High Rate Transmitter Freq	
SR-2	SR-3	25.44 4 .7	2-X2	ט- גר ני	/-Xc		SA-1	SA-2	SA-3	SA-4	SA-5	SA-6		SA-7	SA-8	SA-9	SA-10	SA-11		RS-1	RS-2	RS-3	RS-4	RS-5-6	RS-7	RS-8-9	RS-10	RS-13	RS-12	RS-13	RS-14-15	RS-16	RS-17-18	RS-19	RS-20	RS-21	RS-22	RS-23	
																		9	5	•	4	3		ق	?														

SURFACE LABORATORY INSTRUMENTATION LIST (Continued)

						SAME	SAMPLES/SECOND	۵	
PARAMETER	RANGE/ CHARACTERISTICS	ТҮРЕ	ACCURACY	CKNISE LAUNCH &	PREPARATIOÙ CHECKOUT	DE-ORBIT ENTRY	YAQ	ИІСНТ	SUNSET SUNRISE/
Thermal Control Radiator Temperatures (8) Cold Plate Temperatures (8) Heat Pipe Fluid Pressure (8)	-200° to 150°F -50° to 200°F 0-15 psia	크크로	3% 3% 5%	.00. 100. 100.	1/60 1/60 1/60	0.00	1/900	1/900 1/900 1/900	1/900
Electrical Power Battery Voltage (4) Battery Temperature (4) Battery Current Battery Chorge Current (4)	18-37 vdc 0 ⁰ -120 ⁰ F 0-5 amps 0-2 amps	7777	3 % % % % % % % % % % % % % % % % % % %	8 8 8 8	1/120 1/120 1/120 1/120	<u>0</u> <u>0</u> <u>0</u>	1/900	1/900 1/900 1/900	1/900 1/900 1/900
Command Subsystem FSC Command Detector Lock SLS Command Detector Lock Command Receipt Direct Command Actuate Quantitative Command Transfer	256 Cmds	98 P	7 Bits	.000	1/30 1/30 1/30		1/900		
Terminal Propulsion Source Pressure Regular Pressure (6) Temperatures (7)	0-4500 psia 0-1500 psia -50° to 300°F	로 분 그	3% %				1/3600 1/3600 1/3600	1/3600	1/3600 1/3600 1/3600
Telemetry Subsystem Oscillator Temperature Telemetry Mode Vehicle Time	25° to 150°F	ەەك	3% 4 Bits 10 Bits		1/60 1/60 1/60		006/1	1/900/1	1/900
DC Power ADC Linearity Voltages (3)	18–38 vdc 0–5v	로로	3%		09/L		006/1	1/900 1/900	1/900 1/900
Differential Amp Linearity (3)	0-40 mv	크:	3%		09/1	5	000/1	1/900	1/900
Transducer Voltage Source Cruise Commutator DC Power	0-40 mv 18-38 vdc	<u> </u>	3%	<u>.</u> 8	09/1	<u> </u>	96/	006/	006/1
DS-13-15 Cruise Commutator Differential	0-4 mv	3	3%	.00		<u>e</u> .			
DS-16 Cruise Commutator Mode DS-17-19 Cruise Commutator ADC	0-5V	급	4 Bits 3%	100.		<u> </u>			
DS_20-22 Checkout ADC Linearity Voltages (3) DS_23-25 Checkout Differential Amp Linearity (3)		분 분	3%	,	09/1				
Test Programmer		ā			1 /30				

- A 0	1P-2	Routine in Process	<u>α</u>	! 0	6 Bits		1/30		
		Power Supply (4)		土	3%		1/30		
è		Pyrotechnics (12)		B	•				
	<u>-</u>	Fire Relay							
Ā	(-2	Subsurface Probe Release Initiator		님 :					
ď	PY-3	Redundant Subsurface Probe Release		 Н					
1		Initiator		ā					
ì.	PY-4	Subsurface Probe Extend Initiator		, <u>a</u>					
₫_	-5	Redundant Subsurtace Probe Initiator		٦ 					
		Extend Initiator						_	
ď	PY-6	Subsurface Probe Deploy Initiator							
ď		Redundant Subsurface Probe Deploy	<u> </u>	٦,					
		Initiator							
7	PY-8	Surface Probe Deployment Arm &		BL					
		Fire Relay							
ď	PY-9	Redundant Surface Probe Deployment		BL -					
		Arm & Fire Relay							
<u>6</u>	PY-10	Surface Probe Release Initiator		7:					
4	Y-11	Redundant Surface Probe Release Initiator		<u>۔</u>					
á	Y-12	Surface Probe Extend Initiator		٦ . د					
<u>€</u>	Y-13	Squib Bus		٦.					
6	Y-14	Redundant Squib Bus		<u>ا</u> ا					
á	Y-15	Antenna Release Arm & Fire Relay		ا ا					
<u>6</u>	PY-16	Redundant Antenna Release Arm &		7					
_		Fire Relay							
á	Y-17	Antenna Release Initiator		ב ה					
á	PY-18	Redundant Antenna Release Initiator		- B					
<u>a</u>	Y-19	Atmos. Probe Deploy Arm &		۳ ا					
		Fire Relay		 i					
á	PY-20	Redundant Atmos Probe Deploy Arm		BL					
_		& Fire Relay				-			
á	PY-21	Atmos Probe Release Initiator	_	ָה ה					
á	Y-22	Redundant Atmos Probe Release		- -					
-	•			_			_	_	_

1,3600 1,3600 1,3600 1,3600 1,3600 1,3600

1/3600

1/3600

1/3600

1/3600

1/3600

1/3600

1/3600

1/3600

1/3600

1/3600

B B

밁

Cuteurface Probe Deployment Arm & Fire

Initiator

20

Redundant Atmos Probe Extend Atmos Probe Extend Initiator

PY-23 PY-24

Initiator

1/3600 1/3600 1/3600

Surface Extend Initiator	Redundant Surface Probe Sensor Unlock Initiator Redundant Surface Probe Sensor Unlock Initiator	-10	Address Decoder Entry Address Decoder Entry Driver Output Counter Power Supply Voltage (3) Memory Verification (128 wards by 24 Bits per ward)	Antenna Subsystem Antenna Erection Blevation Gyro, On/Off Azimuth Gyro, On/Off 0 or 28 vdc		Deceleration Gimbal Pos ± 30° Tracking Receiver AGC 0–5 v	Iracking Receiver A Dec U or 28 Tracking Receiver A Ha 0 or 28 Azimuth Servo Electronics Mon 0 or 28	cs Mon	Ha Servo Electronics Mon Deceleration Servo Electronics Mon 0 or 28	n Receive Antenna Reverse	Power Low Gain Transmit Antenna Reverse	Power Low Gain Antenna Deployed
		to 150°F	Commands	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		-		-dc	-dc			
ВГ	명명	1 d a	400±	8 P.	로로	를 로 로 ;	4 4 4	급 :	9 9	로	土	В
		3%	7 Bits 7 Bits 2%		3%	3%%				3%	3%	
		100		60.00	8.8.8	<u> </u>	96.6	00	<u>8</u> 8	.00		
		200	99/1	1/120	27.73	17120	17120	1/120	222	1/30	1/30	
		<u> </u>							<u>. </u>			
1/3600	1/3600	006/1	₩ %	1/600/1/600	1/600	009/1	009/1	1/600	009/1 1/600			1/3600
		1/900/1	1/900/1									
		1/900	1/900			···						

SURFACE LABORATORY INSTRUMENTATION LIST (Continued)

	SCIENCE PARAMETER SAMPLE RATE	Video – 5 lines/sec	Video – 5 lines/sec
	MODE CHARACTERISTICS	2 frames, one each camera, to be completed first morning – each frame 300 elements x 1200 lines.	5 frames (both cameras used) to be completed first afternoon – each frame 400 elements x 400 lines.
A VISUAL IMAGING	MODE	Low Resolution Panoramic Stereo	Medium Resolution

ATMOSPHERIC PROPERTIES	OPERTIES	
MODE	MODE CHARACTERISTICS	SCIENCE PARAMETER SAMPLE RATE
Day/Night	Instruments energized every 15 minutes, operates at all times other than during sunrise/sunset mode.	One/15 minutes*
Sunrise/Sunset	Instruments continuously energized — from one hour prior to sunrise and sunset to one hour after-	One/minute*
*All parameters sampled within	within one minute.	

A ALPHA SPECTROMETER

MODE CHARACTERISTICS

SCIENCE PARAMETER

SAMPLE RATE

One/8 hours.

Eight hour count each sample, 3 samples total, after

surface sampler operation.

MODE
Prepared Sample

Figu

5.4-7-1

~	Z4 GAS ANALYSIS (GAS CHROMATOGRAPH)	Atmos & Subsurface • Eight — 20 minute analysis, three each at sunrise & One/3 secs Sunset, one at noon and one at midnight — subsurface 10 min. Cols 1 & 2 parallel operation then atmos 10 min cols 1 & 2 parallel operation.	Soil Volaties — 4—100 minute analysis. Phased with soil sampler One/6 secs (cols 3 & 4) Analysis — One/3 secs (cols 1 & 2) then 40 min cols 3 & 4 in parallel, then repeat for temp 2.	Calibration Two operations (before and after use) 50 minutes each — cols 1 & 2 in parallel (10 min) & cols 3 & 4 one/6 sec (cols 3 & 4) in Par. (40 min).	S LIFE DETECTION (METABOLISM 1 & 2)	MODE MODE CHARACTERISTICS SCIENCE PARAMETER SAMPLE RATE	Normal Operates to twelve hours after soil samples are in- troduced in situ portion operates to 5 hours after deployment daylight only.	Checkout One 10 min. cycle. (Dry run)	
----------	-------------------------------------	--	--	---	-------------------------------------	---	---	---------------------------------------	--

e 5.4–4 (Continued)

5.4=7

_
٥
2
Ξ
Į.
\mathcal{L}
Н
LIST
Z
ATION
A
Z
NEN.
\supseteq
Ë
S
=
≿
COR
_
ABORA
ō
AB
7
ш
כ
₹
2
SURFACE
~)

15/5 min.	nin.		ARAMETER TE					ETER	. 5 sec
	15/5 min.		SCIENCE PARAMETER SAMPLE RATE	One/15 minutes	One/minute	See below.		SCIENCE PARAMETER SAMPLE RATE	One sample/sec for 5 sec
Operates to 26–2/3 hour after soil samples are introduced.	One 5 min. cycle (dry run)	PERTIES (SUBSURFACE PROBE)	MODE CHARACTERISTICS	Temperature sensors energized every 15 min., all times other than during sunrise/sunset mode.	Sensors continuously energized — from one hour prior to sunrise and sunset to one hour after.	Collects gas samples for gas chromatograph, eight operations total.	ETER	MODE CHARACTERISTICS	Energized every 15 minutes day & night.
Normal	Checkout	A SUBSURFACE PROF	MODE	Day/Night	Sunrise/Sunset	Gas Sampling	<u></u> <u>8</u> SPECTRORADIOM	МОDЕ	Part 1 (Insolation)
		ס∩↓	out SSURFACE PROPERTIES	after soil samples are in-) TERISTICS	after soil samples are in-) FERISTICS gized every 15 min., all unrise/sunset mode.	after soil samples are in-) TERISTICS gized every 15 min., all unrise/sunset mode. rgized — from one hour prior one hour after.	after soil samples are in- CERISTICS Granner, all	ofter soil samples are in- TERISTICS gized every 15 min., all unrise/sunset mode. rgized – from one hour prior one hour after. gas chromatograph, eight	after soil samples are in- CERISTICS

5.4-8-1

One sample/sec for 72 sec for 72 sec for 72 sec per viewing direction	The state of the s
Operates 7 times/day, evenly spaced during daylight hours — 4 viewing directions/operation.	
Part 2	

direction		SCIENCE PARAMETER SAMPLE RATE	See instrumentation list.	
	UISITION	MODE CHARACTERISTICS	Operations total 2 hours. Operations intermittent with sample processor operations interleaved.	Operations (4) total 40 minutes — interleaved with soil sampling.
	ØSOIL SAMPLE ACQUISI	MODE	Soil Sampling	Sample Processing

10 Memory Content Verification – readout entire memory on command

211 Event Parameter — time of event must be known to within 10 seconds. Event occurs at capsule up-date. 12 Time tag to indicate time of occurrance to within 10 min.

Definitions:

HL - Single ended high level - 0 to 5 volts

LL - Double ended low level - 0 to 40 millivolts

D - Digital

BL - Bilevel

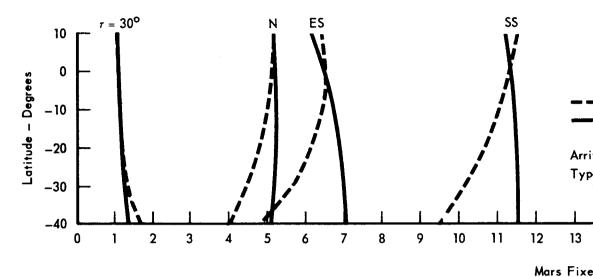
Figure 5.4—4 (Continued)

5:4-8

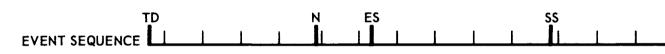
5,4-8-2

SCIENCE SEQUENCE MORNING LANDING

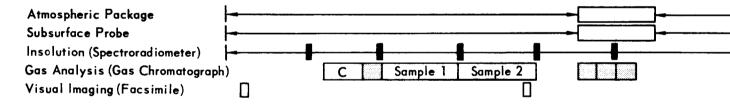
A. SOLAR - REFERENCED TIMES - SEQUENCE FOR 1973 MISSION CONSTRAINTS



B. SCIENCE SEQUENCE COMPARED WITH EVENT SEQUENCE FOR PREFERRED MORNING LANDING SITE (0° L



1. Solar Event Referenced Science Sequence



2. Touchdown Referenced Science Sequence

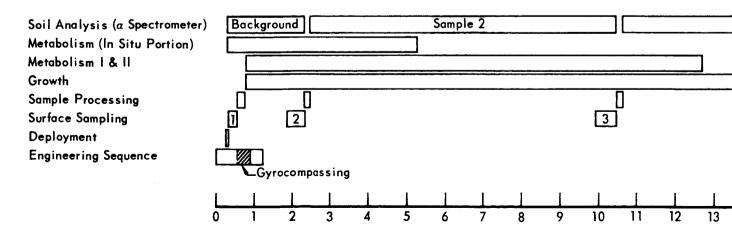
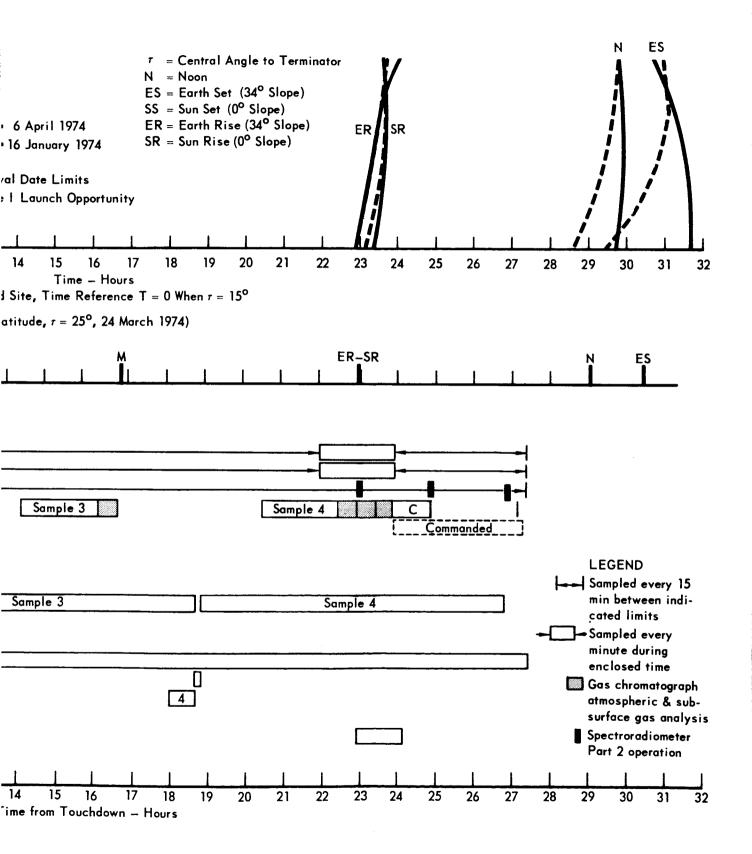


Figure 5.4-5



5.4-9-2

SLS-DHS DATA COLLECTION AND TRANSMISSION MODES

MISSION PHASE	DATA CONTENT	DATA CHARACTERISTICS	S
Launch and Interplanetary Cruise	Minimal data monitoring via hardline to SC-DHS. Primary SLS-DHS inactive. Data derived from cruise commutator.	2.8 bps Same data as in PCM planetary cruise 0.28 bps Same data as in phase, but at 1/PCM rate.	plase. Iaunch
Pre- Separation Checkout	Data derived from both the data system output and from test programmer. Hardline to SC-DHS.	PCM	
De-Orbit and Entry			
Landed Day	Data collection mode. All data except TV.	14.4 bps Data collection PCM	rate
	Data collection mode. All data including TV.	12K bps Data collection PCM	rate
	High rate data transmission mode.	1200 bps Transmitted dat be either TV pl other daytime d only stored nigh PSK/PM data.	us all ata or
	Low rate transmission mode	PSK/PM	
	Low rate primary mode	0.5 bps, Low rate primar MFSK uncompressed o	•
Landed Night	Data collection mode.	4.3 bps	

The high-rate link requirements can be met in many ways. We have considered direct links to Earth, using high gain antennas, and also relay links to the orbiting spacecraft. The preferred approach is the direct link, since the optimum relay link orbit choices do not coincide with those for the spacecraft mapping mission.

Choice of a direct link was followed by other studies as shown in Figure 5.4-2. These included antenna subsystem implementation, as discussed in Section 5.4.6, and modulation and coding techniques. PSK/PM and convolutional coding (with sequential decoding) were chosen to optimize the link efficiency as much as the state-of-the-art would permit.

The resultant hardware configuration was then analyzed in detail, resulting in basic system level parameters, size, weight, efficiency, and failure modes and effects, as discussed in Section 5.4.6 and 5.4.7.

The low-rate link, intended as a highly survivable backup, presents a unique design problem. The effective radiated power required to maintain a coherent link precludes the use of low power and omni-directional antennas, both of which are necessary for this link. Therefore, we chose a non-coherent multiple frequency shift keying (MFSK) technique, thus avoiding the power penalty. Since this technique is unproven in this application, where the data rate is small compared to the frequency uncertainty, a considerable amount of analysis was required to determine acquisition techniques, times, and the required signal-to-noise ratio. These study results are presented in Section 5.4.3 and indicate the preferred receiver characteristics as well as the transmitter design.

The telemetry data acquisition function is a primary part of the TCM design. In Section 5.4.9 through Section 5.4.13 we discuss the many configurations and techniques that were studied. The selected approach provides a high degree of versatility and optimum data formatting techniques. Interlaced tube formats were selected for engineering and periodic science data, to provide optimum efficiency and tolerance of changes. Burst tube formats were chosen for the high-data-rate and aperiodic experiments.

5.4.2 <u>High Rate Link Characteristics</u> - The high rate link provides the primary means of communication from the SL to Earth. Because we must transmit a large quantity of information (5 x 10^6 bits per day minimum) over a range of 250 x 10^6 to 2.85 x 10^6 km it is necessary to provide an effective radiated power (ERP) on the order of 63 dBm. The selected design consists of a 20 watt transmitter and a 36 inch diameter parabolic antenna which has a peak gain of 24.3 dB.

This section discusses the selection of modulation and coding techniques to maximize the link efficiency within the constraint of compatibility with the DSN configuration planned for 1973. The preferred system uses PCM/PSK/PM modulation and convolutional coding with sequential decoding.

5.4.2.1 Modulation Technique - Compatibility with the DSN in terms of data reception and two-way coherent Doppler tracking has been assured by the use of a square wave subcarrier conveying PSK data which is phase modulated onto an S-band carrier with a modulation index of 1.15 radians. The subcarrier frequency is 3600 Hz and is coherent with the data stream.

The selected modulation index retains enough carrier power to ensure a signal to noise ratio of 16 dB in a carrier tracking bandwidth of 5 Hz to allow Doppler tracking and data demodulation.

For the bit rates selected (300, 600 and 1200 bps) synchronization can be accomplished with either a squaring loop synchronizer or the unique synchronizer developed for the Capsule Bus and Entry Science Package relay links. The ambiguities in synchronization can be easily resolved with transition detecting circuitry of the conventional type.

- 5.4.2.2 <u>Coding Techniques</u> The purpose of using coding in the telecommunication system is to maximize the efficiency of the link. This increase in efficiency can be used for either reducing the effective radiated power (ERP) requirements if a fixed data rate is required or it can be used, for a fixed amount of available ERP, to maximize the data rate of the link. In order to achieve this efficiency an encoder is required at the transmitter and a decoder at the receiver. This section evaluates the characteristics of various coding techniques. Sequential decoding with convolutional coding has been selected for use.
- 5.4.2.2.1 Evaluation Criteria The three criteria used in the evaluation are:
 (1) Efficiency (reduction in power requirements achieved by using the coding technique), (2) simplicity of the coding equipment, and (3) effects on the (Earth) decoding equipment. Of the evaluation criteria, the most important is efficiency.

The selection of a coding technique involves a tradeoff between additional complexity and transmitter power requirements. The next most important factor is the extent of complexity of the encoding hardware. Use of an extremely complex encoder would not be warranted. The least important factor is the complexity of the decoding equipment. However, if complexity in the ground receiving station can provide improved system performance, it becomes an attractive approach to improve link margin.

5.4.2.2.2 <u>Alternate Approaches and Significant Characteristics</u> - Five candidate types of codes were considered in the study. These are:

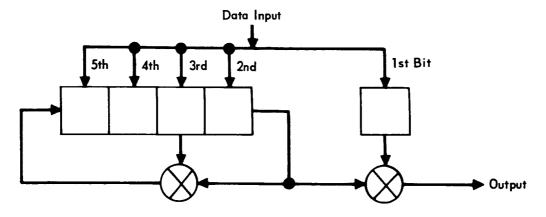
- a. Block codes with bit by bit detection,
- b. Block codes with detection over the word,
- c. Block codes used in a concatenated fashion,
- d. Hybrid coding, in particular, convolutional coding followed by block coding and,
- e. Convolutional coding with sequential decoding.

Reference 5.4-1 describes the characteristics of a, b, and c in detail. Convolutional codes are also discussed in Reference 5.4-1, but much new information has been obtained since its publication and is contained in Reference 5.4-3.

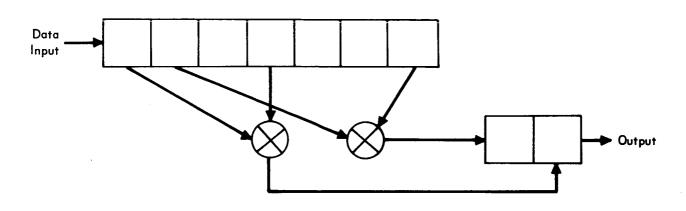
Because of the inefficiency of the block codes using bit-by-bit detection, they will not be considered further. Concatenated codes do not hold much promise for this system. Briefly, the concatenated code concept is as follows: Perform block coding on the data stream, and having encoded the data stream, perform block coding on it again, but not necessarily with the same coding scheme. This can be quite efficient in terms of achieving extremely low error rates. However, for the error rates of interest here, insignificant improvement over straight block coding with word detection is achieved while the complexity of the system is increased. This technique will therefore not be further considered in this section. For further information the reader should consult Reference 5.4-4. Only techniques b, d, and e will be considered below.

Encoder Characteristics - The encoder functional diagrams are shown in Figures 5.4-7 and 8. As can be seen the biorthogonal encoder and convolutional coder without interleaving are both relatively simple. The hybrid encoder is more complex. However, using integrated circuit modules, the hardware involved is not too complicated. The most complex (i.e., the encoder requiring the greatest amount of hardware) is the convolutional coder followed by an interleaver.

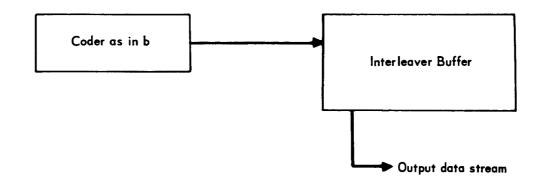
ENCODER BLOCK DIAGRAMS



(a) BI-ORTHOGONAL ENCODER



(b) CONVOLUTIONAL CODER: CONSTRAINT LENGTH = 7, RATE = 2



(c) CONVOLUTIONAL CODER WITH INTERLEAVING

Figure 5.4-7

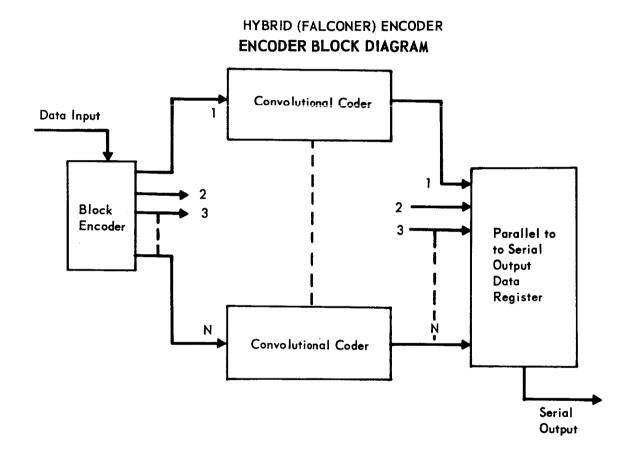


Figure 5.4-8 5.4-15

Interleaver Requirements for Sequential Decoding - Whenever a carrier or subcarrier tracking loop loses lock the link experiences burst errors. This degradation, due to coherence loss, can be reduced by interleaving the bits in the transmitted data stream. This performs the function of converting the channel from one with memory to one without memory and improves channel efficiency (see Reference 5.4-3).

In order that the burst errors do not disrupt the decoding operation, interleaving can be introduced such that adjacent transmitted symbols actually occur in real time intervals separated by $T = \frac{1}{2B_L}$ where $2B_L$ is the tracking loop two-sided bandwidth.

Interleaving can be performed to any degree. If we seek to ensure a time separation between all adjacent data bits we must insert a time delay of T between them. One way is illustrated in Figure 5.4-9. As shown the data would be read into a buffer a row at a time and then read out a column at a time.

If adjacent transmitted symbols are to be spaced in time by T we have,

$$T_s = \frac{T_b}{V}$$
 and $N = \frac{T}{T_s} = \frac{V}{T_b 2B_L} = \frac{VR_b}{2B_L}$

where T_s = transmitted symbol period T_b = transmitted data bit period = $\frac{1}{R_b}$

v = rate of encoder

In order to accumulate N inputs to a column we must let k=N. The capacity of the buffer for this condition is:

Capacity =
$$N^2 = \left(\frac{VR_b}{2B_L}\right)^2$$

Figure 5.4-10 presents the buffer requirements for three operating symbol rates and three loop bandwidths. As can be seen the capacity requirements increase enormously as the data rate rises or the loop bandwidth drops.

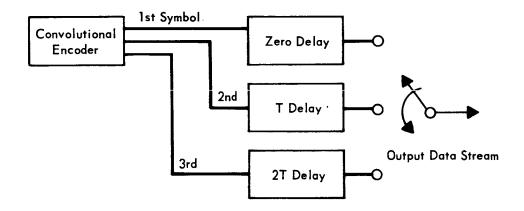
Minimum Interleaver Implementation - The simplest interleaver implementation requires enormously reduced hardware requirements. Its implementation is as follows. Assume a rate-three encoder and delay the first bit by zero time, the second bit T seconds, and the third bit by 2T seconds. The output of the three delay circuits can then be readout sequentially to provide a symbol stream of adjacent symbols in real time which are now spaced in time by T seconds. Figure 5.4-9 illustrates the minimum interleaver system for T = $3T_s$ where T_s = symbol period.

INTERLEAVER CHARACTERISTICS

1, 2, 3,	k
k+1,	2k
2k + 1,	3k
	•
	•
•	•
(N-2)k+1,	(N-1)k
(N-1)k+1,	Nk

1, 2, 3,
$$\cdots$$
 k, \cdots 2k, \cdots Nk Input Data Stream
1, k+1, 2k+1 \cdots 2, k+2, 2k+2, \cdots Nk - 3, NK - 2, Nk - 1, Nk Output Data Stream

Interleaver Data Buffer
(a) Maximum Interleaver



(b) Minimum Interleaver

Figure 5.4-9

MAXIMUM INTERLEAVER REQUIREMENTS

Capacity =
$$N^2 = \left(\frac{VR_b}{2B_1}\right)^2$$

		SYMBOL RATE							
	1	00 bp:	s	500 bps			1000 bps		
	2	2 B _L , Hz		2 B _L , Hz		2 B _L , Hz			
	12	12 5 1		12	5	1	12	5	1
Capacity N ²	600 Bits	3.5K Bits	95K Bits	16K Bits	90K Bits	2.2M Bits	60K Bits	350K Bits	9M Bits

Figure 5.4-10

5.4-17

There is a difference between this interleaver and the maximum interleaver. The maximum interleaver of places all symbols, within any real time period (T), mutually spaced in the transmitted symbol stream by at least T seconds. The minimum interleaver has the characteristics such that in any time period T, there will be symbol outputs (for any chosen symbol and position) from the same position which occurred only T- seconds previously. When the symbols are unscrambled at the receiver there will be $T/T_{\rm S}$ successive symbols in error in the first position in some time period T. The same will be true for symbols in the second and third positions in different time slots of length T.

The only work performed to data on simulation with interleaving appears to have been performed by Dr. Jacobs of the University of California at San Diego and his students. The work, however, is not sufficiently detailed to show the exact variation of coherence loss versus degree of interleaving. What does appear to have been shown is that, with complete interleaving (as shown in Figure 5.4-9) and with T equal to the error burst period, the coherence degradation is reduced to approximately 0.1 db for a signal to noise ratio of 13dB.

The storage requirements are quite large for a data rate of 1200 bps. It is believed (personal communication from Jacobs) that the degree of interleaving shown in Figure 5.4-9 will reduce coherence loss the same amount. This defines the storage requirements for a data rate of 1200 bps. The storage register length is 192 for a $2B_{\rm T}$ of 12 Hz, 480 for a $2B_{\rm T}$ of 5Hz and 2400 for 1Hz.

This appears to be a very small amount of hardware to achieve an improvement of 0.9 dB in system power efficiency and should be used. However, it has not been demonstrated that this degree of interleaving is indeed adequate and a study is presently underway by Dr. Jacobs to settle this question. The results of the study should be available within a year.

Decoder Characteristics - The simplest decoder is probably the block code (biorthogonal) decoder. It can be provided as a special purpose piece of equipment or it can be programmed on a computer (see Reference 5.4-1). Even this decoder, however, is a relatively complex unit. The sequential decoder for the convolutional coding and the hybrid system decoder would be implemented only on a computer although the sequential decoder can be implemented as a special purpose compute. Since all three decoders are complex, none has much advantage in this respect. However, in order of increasing complexity, they rate as: biorthogonal decoder, sequential decoder, and hybrid decoder.

Of particular interest in decoder characteristics are the simplifications to

the Fano decoding algorithm described by Jacobs in References 5.4-3 and 5.4-4. An optimum algorithm is desired in order to minimize overflow probability. Briefly, the first simplification is to eliminate the variable θ from the algorithm θ . The other simplifications relate to restricting some of the possible motions a computer would follow in searching the tree for the proper code. Gallager has suggested an additional change which amounts to always searching the θ branch first rather than the best branch. This would seem to permit a simple implementation, but require a longer search; however, it has been shown that a best branch search can be accomplished without additional complexity. Better decoding algorithms do not appear to exist.

Power Requirements - The efficiency of the link is improved if the power requirement for data transmission at a fixed rate is reduced. A direct measure of the power requirements in the $\frac{ST_b}{N_o} = \frac{Energy\ per\ Data\ Bit}{Noise\ Power\ Density}$. This is discussed in References 5.4-1 and 5.4-2 for the biorthogonal codes, in Reference 5.4-3 for sequential decoding, and in Reference 5.4-5 for hybrid decoding. The power requirements for biorthogonal coding and sequential decoding are derived below.

Sequential Decoding - On the basis of the data in References 5.4-3 and 5.4-4 let K = 24, r = 3; we obtain:

	Cause	Requirement or Degradation
	Theoretical Minimum	- 1.6 dB
	Quantization, $Q = 8$	+ 0.2 dB
	Rate, $r = 3$	+ 0.6 dB
	Sync and Tail	+ 0.06 dB
	Reference Incoherence, SNR = 13 dB	$+ 1.0 \text{ dB}^{(1)} + 0.5 \text{ dB}^{(2)} + 0.1 \text{ dB}^{(3)}$
	Degradation 2 of $\alpha > 1$	+ 0.14 dB
	$\alpha = 1$	+ 3.0 dB
(1)	Without interlegating CND - 12 JB	+ 3.4 dB + 2.9 dB + 2.5 dB

- (1) Without interleaving, SNR = 13 dB
- (2) Without interleaving, SNR = 16 dB
- (3) Without interleaving, SNR = 19 dB; or with interleaving, SNR = 13 dB

Biorthogonal Coding (16, 5)

Cause	Requirement or Degradation
Theoretical Minimum	+ 3.3 dB
Quantization, $Q = 8$	+ 0.5 dB

 $^{^{0}}$ is a variable in memory which determines when the running threshold would be tightened (see Reference 5.4-5).

 $^{^{2}}$ lpha is the exponent in the Pareto distribution for the sequential decoding computational time.

(Continued)

Cause

Synchronization

Reference Incoherence

Requirement or Degradation

+ 0.6 dB

__Δ

 $4.4 dB + \Delta$

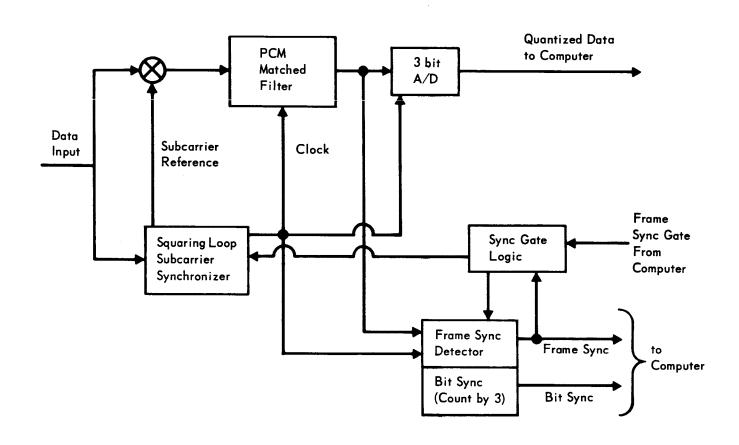
The magnitude of the data power degradation caused by the incoherent reference (loss of carrier lock) for biorthogonal coding is not known. There is no doubt that it will degrade performance. What must be done is to increase the carrier power to the point that loss of lock occurs sufficiently infrequently that the degradation is negligible. It would seem that a SNR in the carrier loop of the same order of magnitude as used for sequential decoding (i.e. about 16 dB)would be adequate. This is a high carrier power requirement but, what is more important, is that total power requirements are made as low as possible, (i.e., data plus carrier power). For carrier loop bandwidths of 12 cps or less and data rates of 300 bps or higher the ratio of data to carrier power requirement is 10 dB or more. In this case, the system improvement available is the data power reduction of 1.0 dB which, all things being equal, is still worth achieving. For any low data rate we must determine the magnitude of Δ . In any case, sequential decoding will be superior by 1.0 dB or more.

<u>Detection Equipment Characteristics</u> - The modulation technique to be used on the high data rate link is PCM-NRZ data modulation PSK on a square wave subcarrier. The subcarrier frequency selected should be equal to the transmitted symbol rate or some integral multiple of it. A block diagram of the subcarrier demodulation and sequential decoding equipments is shown in Figure 5.4-11.

The squaring phase lock loop has been analyzed (Reference 5.4-6) together with an evaluation of the required ratio of data rate to loop bandwidth vs. the resultant data degradation (Reference 5.4-7). This information has been compactly summarized in Reference 5.4-8 from which we find that, for a data rate (R_b) to one sided loop bandwidth (B_L) ratio of 90, the data degradation is 0.25 dB. This represents a mean value of loop error of approximately 13.5° for which case the signal to noise is about 10 dB. It was stated above that the signal to noise in the two sided loop bandwidth should be 16 dB (without interleaving) in order to keep the degradation due to the burst errors below 0.5 dB. This requires a R_b/B_L of 360 (4 x 90) for $2B_L$ = 1 cps, R_b = 180 bps. Our operating data rates will all be considerably higher than this.

Figure 5.4-11 presents a block diagram of the data demodulation equipment

HIGH RATE LINK DATA DEMODULATOR BLOCK DIAGRAM



interface between the receiver output and the compute. The block diagram is self-explanatory except perhaps for the sync gate logic. In this diagram the sync gate logic is sensing the polarity of the frame sync detector output to resolve the ambiguity of the subcarrier as well as providing the standard sync gate operations during frame sync search and in lock modes.

The detection equipment characteristics are presented in detail in Reference 5.4-1 and -2.

5.4.2.3 <u>Comparison of Alternate Coding Techniques</u> - Figure 5.4-12 summarizes the comparison of the alternate coding techniques evaluated above. As shown the hybrid coding scheme cannot be seriously considered at this time because it is not sufficiently well defined; it is however the most efficient technique. The biorthogonal technique has the simplest encoder and possibly the simplest decoder. It will also be flown on the Mariner '69. However, the sequential decoding scheme is to be used on the forthcoming Pioneer satellites and the encoder and decoder are only slightly more complex than those for the biorthogonal coding system.

Considering these facts and because sequential decoding is at least 1 dB more efficient, it is recommended that sequential decoding with convolutional coding be used.

The characteristics of the encoder are as follows:

K = constraint length = 24

v = rate = 1/3

A systematic code should be used, i.e. the first chip of every 3 chip data symbol will be identical to the data bit. Dr. Jacobs has shown that such a code is as efficient as non-systematic codes and in addition the computer requirements are enormously reduced.

CODING TECHNIQUES COMPARISON

TECHNIQUE	ENCODER	DECODER	$ST_b/N_o For$ $P_b = 5 \times 10^{-3}$	DEVELOPMENT STATUS
1 Block Code Biorthogonal Word Detection K = 5	Feedback Shift register of length k	Special purpose detection equipment as described in Ref. 1, or computer decoder with special purpose subcarrier demod., bit synch, and A to D converter	≥ 4.4 dB	To be used on Mar '69 by JPL
2 Sequential Decoding $K = 24$ $v = 1/3$	One length K shift register, one length v shift register and v mod - 2 adders	Special purpose sub- carrier demod, bit synchro- nizer, A to D convertor followed by computer de- coder	< 3.4 dB	Planned for future pioneer mission by ARC NASA
3 Hybrid (Falconer) Coding	N convolutional en- coders preceeded by a block encoder on N symbol alphabet	N sequential decoders in parallel followed by block code decoder implemented as computer program	Not calculated. Has been shown to operate 1 dB better than sequen- tial decoding of comparable design	Experimental state
Comparative Rating	1 - 2 - 3	1 - 2 - 3	3 - 2 - 1	1 - 2 - 3

5.4.3 <u>Low Data Rate Link</u> - The purpose of the low data rate link is to provide a primary link prior to initiation of high data rate link operation and a back-up mode of operation should the high data rate link fail. The data will contain engineering and low rate science data.

In order to completely define the Low Data Rate Link three phases of study were defined. The first phase was directed toward defining a modulation technique which would permit continuous operation at a low data rate. It was concluded that multiple frequency shift keying (MFSK) modulation is the best choice to maximize efficiency on the link.

A second study was made to compare the efficiency of transmitting continuously at a low rate with that of transmitting in short bursts at an increased rate. The study showed that continuous transmission at a low rate is more efficient.

An evaluation of receiver design was conducted to determine the type best suited to handle an MFSK data link. It was concluded that a spectral analysis fast Fourier receiver is the most efficient and versatile of those compared. 5.4.3.1 Modulation Selection - It is desired that the low rate link operate with no more than 5 watts transmitter power and an antenna gain on the order of -1 dB (hemispherical coverage). At the maximum operating range expected for the 1973 VOYAGER mission the received S/N_2 at the DSIF communication links have been coherent systems because, at their operating data rates, coherent techniques have been the most efficient. In order to have a coherent link however, we must provide a coherent carrier. In this case the carrier must operate with a minimum receiver phase lock - loop bandwidth of 5 Hz and a minimum signal-to-noise ratio in the range of 6 to 9 dB. To establish the coherent carrier alone, disregarding the data power requirements for the moment, we must have a received S/N_{Ω} of from 13 dB to 16 dB. Because we do not want to reduce the antenna coverage, this represents a transmitter power of from 30 watts to 60 watts to satisfy the coherent reference requirements above. Obviously this is unacceptable. Even if it were possible to reduce the receiver loop bandwidth to 1 Hz the power required is between 6 to 12 watts which is still excessive.

The preceding discussion has ignored the question of the required system bandwidth because of oscillator instabilities, Doppler and Doppler rates. Because Doppler and Doppler rates must be accommodated by any system we will disregard them for the moment. Oscillator instabilities, on the other hand, become of primary importance for this low data rate link. Considering again for the moment a coherent system, a large loop bandwidth 'tracks out' the oscillator instabilities and they

have small effect on system power requirements. As the system bandwidth drops and approaches the oscillator phase noise bandwidth it becomes incapable of tracking the oscillator instabilities. This problem is encountered in both coherent and non-coherent systems but is much more severe in a coherent system.

Because of all these various considerations it becomes apparent that non-ccherent modulation techniques must be used for maximum efficiency. Studies of systems displaying the above defined characteristics have led to the conclusion that the optimum technique is a noncoherent operation with orthogonal signals (See Reference 5.4-9, -10, -11 and -12). It must be pointed out however that these previous results indicate power requirements which are either excessively optimistic (e.g. Reference 5.4-11) or pessimistic (References 5.4-10 and -12). A more exact analysis has been performed which, it is believed, more truly represents the characteristics of the system (See Section 5.4.3.4).

MFSK vs Orthogonal Coded Binary FSK - To transmit orthogonal non-coherent signals either multiple frequency orthogonal signals (MFSK) or orthogonal binary codes on non-coherent FSK may be used. An analysis comparing the two was performed with the assumption that an optimum receiver is used for the binary system and a suboptimum receiver (correlator plus envelope detector) for the MFSK system. The conclusions drawn were:

- a. For these conditions approximately 3 dB more power is required for the binary system.
- b. The binary system is less sensitive to frequency mistuning by a factor $^{(1)}$

$$F_1 = \frac{\sin^2 (2\pi\Delta f \frac{T_s}{k2^k})}{\sin^2 (2\pi\Delta f Ts)} \frac{1}{k2^k}$$

 Δf = frequency offset

c. The MFSK system is less sensitive to timing offset by a factor

$$F_2 = \frac{1}{k2^k} \cdot$$

The system characteristics are tabulated in Figure 5.4-13.

In Section 5.4.3.4 it is shown that the MFSK system degradations will be on the order of 0.5 dB each because of frequency and timing offset. At least 2 dB less power is required for suboptimum MFSK than for perfect binary orthogonal coded FSK. Based on these results the selected modulation technique is MFSK.

⁽¹⁾ These parameters are defined in Figure 5.4-13.

COMPARISON OF ORTHOGONALLY CODED BINARY FSK vs. MFSK

SYSTEM/ PARAMETER	FSK, ORTHOGONAL BINARY CODE	MFSK
Coding Charac- teristics	M = Number of binary code = 2^k M = Chips per code k = Data bits per code $T_b = Bit period$ $T_c = \frac{T_b}{2^k} = \frac{T_s}{k2^k} = Chip period$	M = Tones or symbols = 2 ^k k = Data bits per symbol T _b = Bit period T _s = kT _b = Symbol period = k2 ^k T _c
Receiver and Error Rates	Optimal Non-Coherent Receiver $P_{B} < \frac{1}{2} \exp - \left[\left(\frac{ST}{N_{o}} \frac{ST_{s}}{8N_{o}} - \frac{R}{s/N_{o}} \right) \right]$ $= \frac{M}{2} \exp - \frac{ST}{N_{o}} \frac{ST_{s}}{8N_{o}}$	Spectra; Analysis Detector $P_{B} < \frac{1}{2} \exp \left\{ -\frac{ST}{N_{o}} E' \left(R \right) \right\}$ Sub Optimal Decoder $P_{B} < \frac{M}{2} \exp \left[-\frac{ST}{N_{o}} \left(\frac{ST_{s}}{4N_{o}} \right) \right]$
Degradation Characteris tics	Mistuning: $\Delta f = \text{Frequency offset}$ power loss $\alpha = \frac{\sin^{-2}(2\pi\Delta f T_c)}{(2\pi \Delta f T_c)^2}$ Timing: $\tau = \text{Timing error}$ power loss $\alpha = \frac{\tau}{T_c} = \frac{\tau k 2^k}{T_s}$	Mistuning: $\Delta f = \text{Frequency offset}$ power loss $\alpha = \frac{\sin^{-2}(2\pi \Delta f T_s)}{(2\pi \Delta f T_s)^2}$ Timing: $\tau = \text{Timing error}$ power loss $\alpha \frac{\tau}{T_s} = \frac{\tau}{k2^k T_c}$

5.4.3.2 <u>Data Rate Optimization</u> - Section 5.4.3.1 established the fact that MFSK is the optimum modulation technique for continuous operation at a data rate from 0.5 bps to 10 bps. However, the question arises whether or not another choice involving "burst transmission" with a proven method of modulation suitable for the higher power short period operation might be optimum. This choice is evaluated below for three data quantities: 28,800 bits, 86,400 bits, and 288,000 bits. For a continuous minimum rate link the data rates are 1 bps, 3 bps, and 10 bps respectively, assuming an 8 hour communication period.

<u>Design Approaches and Significant Characteristics</u> - Two modulation techniques are considered. The first is a MFSK system, M = 16, operating for 8 hours at a constant data rate. The second is a coded PSK/PM system operating for a short period of time (burst transmission) but at data rates of 10 bps and above.

The parameters considered in this study are listed below:

- a. Weight of power output device
- b. Weight of power supply (battery weight)
- c. Development status of power output device
- d. Antenna breakdown
- e. Utility (availability of data)
- f. Acquisition Time
- g. Reliability

Figure 5.4-14 lists the required transmitter powers for the various DSIF receiver bandwidths for the PSK/PM system.

Antenna Breakdown - McDonnell's tests on an exposed S-Band helix in three atmospheres have shown limiting power handling capabilities of 160 watts in air, 130 watts in VM-2, and 100 watts in VM-4. Power handling capability can be improved significantly by immersing the radiator in a dielectric material. Tests on the Mercury S-Bank antenna -(a fused silica filled, cavity backed helix)-resulted in breakdown at power 10 times higher than on an exposed helix. However, the selection of dielectric material in this antenna is critical, since the antenna efficiency is reduced by dielectric losses.

Weight and Power Required for Storage - For an assumed constant rate of data generation we can say that a 14K bit memory for storing nighttime data is required for the 1 bps link. If burst transmission is used, as much as a 28K bit memory may be required. The approximate weight and power required for the 14K bit memory is

REQUIRED TRANSMITTER POWER FOR VARIOUS DSIF RECEIVER BANDWIDTH

DSIF RECEIVER	REQUIRED TRANSMITTER POWER, WATTS				TRANSMITTED ENERGY, WATTS-HR dB*			
BANDWIDTH 2B _{Lo} Hz	UN 10 bps	CODED 100 bps	COD 10 bps	ED 100 bps	UNC 10 bps	ODED 100 bps	C0 10 bps	DED 100 bps
1	115	890	63	316	19.7	18.5	17.1	14.0
5	186	1000	105	407	21.6	19.2	19.2	15.2
12	234	1200	158	490	22.2	19.4	20.8	16.0

^{*} For transmission of 28,800 bits
For transmission of 86,400 bits add 4.8 dB

For transmission of 288,000 bits add 10 dB

Assumed Link Parameters
Transmitter Antenna Gain: 0 dB
Range: 2.5 x 10⁸ km at 2295 MHz
DSIF: 210 ft Antenna, Maser Preamp

Convolutional coding with a sequential decoder

3 pounds and 1.4 watts whereas, for the 28K bit memory, it is 5 pounds and 2 watts. Since the difference in weight (2 lbs) and power (0.6 watts) are both small, the added weight and power for burst transmission will be neglected.

Transmitter Power and System Weight - Assuming zero dB antenna gain and convolutional coding with sequential decoding on the PSK/PM links we can define the transmitter power and weight requirements. It is assumed that the DSIF receiver loop bandwidth is 5 Hz minimum because it has been specified that narrower loops will not be implemented by 1973.

Figures 5.4-15, -16, and -17 present a comparison of the characteristics of the systems for the three assumed data loads. The receiver loop bandwidth has been optimized at 5 Hz for minimum power requirements. The recommendation in each case is clearly the use of MFSK.

5.4.3.3 <u>Backup Capability</u> - The baseline low data rate link can provide a backup capability for low rate compressed science data. It cannot however back up the total high rate link data requirement regardless of any special techniques (e.g. compression) which might be used. Possible high rate science backup links are discussed in Section 5.4.4.

5.4.3.4 MFSK Receiving System - The low data rate backup link is power limited. As discussed previously, MFSK modulation has been selected so as to maximize the data rate. However, the best practical receiver design has not been previously defined. A study was therefore undertaken to evaluate several possible receiver implementations.

Receiver Functional Requirements - The objective of the MFSK receiver is to determine which of M (e.g. M = 16) tones was sent over a communication link with a required degree of reliability (e.g. $P_b \triangleq \text{probability of bit error} \leq 5 \times 10^{-3}$). Since the data rate is less than one bit per second, an MFSK symbol will be about four seconds long. Thus for a standard optimum non-coherent (in phase and quadrature) receiver, the oscillator instabilities and uncompensated doppler effects have to be less than a small fraction of 0.25 Hz. This small frequency deviation is clearly impossible with present technology and highly unlikely in the near future. Thus the receiver must cope with the problem of frequency uncertainties on the order of the data bandwidth.

There are several reasonable models for the frequency instabilities involved. One possible model assumes the oscillator to be a perfect sinusoid whose frequency jumps randomly from symbol period to symbol period according to some probability density over any time period (T = 4) at a data rate of 1 bps for M = 16.

COMPARISON OF ALTERNATE APPROACHES FOR 28,800 BITS REQUIRED

FUNCTIONAL AND TECHNICAL DESIGN	MATRIX	IX OF DESIGN APPROACHES SELECTION				
REQUIREMENTS	NO. 1	NO. 2	NO. 3	SEEECHOR		
Emergency transmission of 28,800 bits of data over direct S-band link with antenna gain of 0 db	MFSK M = 16 1 bps 8 hours	Coded PSK/PM 10 bps 48 min. 2B _{Lo} = 5 Hz	Coded PSK/PM 100 bps 4.8 min. 2B _{Lo} = 5 Hz	Selected Approach		
Trade Considerations Weight of power output device plus power supply (batteries)	40 lb.	55 lb.	178.5 lb.	1-2-3		
Development status of power output device	Available (10 watts)	Feasibility Study (100 watts)	No Study (400 watts)	1-2-3		
Antenna Breakdown	Negligible	Possible Difficulty	Major Problem	1-2-3		
Utility	Constantly Available	Available 48 min.	Available 4.8 min.	1-2-3		
Acquisition Time	_	Minutes	Minutes	Insufficient Data		
Reliability	_	_	_	No Data		

COMPARISON OF ALTERNATE APPROACHES FOR 86,400 BITS REQUIRED

FUNCTIONAL AND TECHNICAL DESIGN	MATRI	X OF DESIGN APP	SELECTION		
REQUIREMENTS	NO. 1	NO. 2 NO. 3] SELECTION	
Emergency Transmission	MFSK M = 16	Coded PSK/PM	Coded PSK/PM	Selected Approach	
of 86,400 bits of data over direct S-band link with antenna gain at 0 db	3 bps 8 hours	10 bps 2.4 hours 2B _{Lo} = 5 Hz	100 bps 14.4 min. 2B _{Lo} = 5 Hz	No. 1	
Trade Considerations					
Weight of power output device plus power supply (batteries)	49 lb	73 lb	190 lb	1–2–3	
Development status of power output device	Available (20 watts)	Feasibility Study (100 watts)	No Study (400 watts)	1-2-3	
Antenna Breakdown	Negligible	Possible Difficulty	Major Problem	1-2-3	
Utility	Constantly Available	Available 2.4 hours	Available 14.4 min.	1–2–3	
Acquisition Time	_	Minutes	Minutes	Insufficient Data	
Reliability	_	_	-	No Data	

COMPARISON OF ALTERNATE APPROACHES FOR 288,000 BITS REQUIRED

FUNCTIONAL AND TECHNICAL DESIGN	MATRIX	SELECTION		
REQUIREMENTS	NO. 1	NO. 2	NO. 3	SELECTION
Emergency Transmission of 288,000 bits of data over direct S-band link with antenna gain of 0 dB	MFSK M – 16 10 bps 8 hr	Coded PSK/PM 10 bps 8 hr 2B _{Lo} = 5 Hz	Coded PSK/PM 100 bps 48 min 2B _{Lo} = 5 Hz	Selected Approach
Trade Considerations Weight of Power Output Device Plus Power Supply (Batteries)	68 lb	100 Іь	210 ІЬ	1–2–3
Development Status of Power Output Device	Development Study (50 watts)	Feasibility Study (100 watts)	No Study (400 watts)	1-2-3
Antenna Breakdown	Negligible	Possible Difficulty	Major Problem	1-2-3
Utility	Constantly Available	Constantly Available	Available 48 min	1 or 2–3
Acquisition Time	-	Min	Min	Insufficient Data
Reliability	-	_		No Data

The uncompensated doppler and temperature variations can be accounted for by assuming a drift of the center frequency. In our studies (Reference 5.4-13) it was shown that the optimal receiver (neglecting drift) for this model determines M decision variables z_j ($j=1,\ldots,M$) and decides the tone sent by finding the "j" corresponding to the largest z_j . The decision variables were obtained as:

$$Z_{j} = \int_{-\infty}^{+\infty} (a(\omega)) \cdot P(\omega - \omega_{j}) d\omega \qquad (1)$$

where $P(\omega - \omega_j)$ = probability density of "jumping" frequency about nominal center frequency ω_i .

$$a(\omega) = \left\{ \int_0^T s(t) \cos \omega t \, dt \right\}^2 + \left\{ \int_0^T s(t) \sin \omega t dt \right\}^2$$
 (2)

where s(t) is received signal plus noise.

For small signal to noise ratios, the non-linear operation in equation (1) is equivalent to

$$Z_{j} = \int_{-\infty}^{+\infty} a(\omega) P(\omega - \omega_{i}) d\omega \qquad (3)$$

This receiver has an interesting interpretation. The function, $a(\omega)$, can be seen to be the <u>amplitude</u>-spectrum-squared of received signal and the decision variables z_j are obtained by appropriate weighting and summing of these spectral values. Thus, this receiver has M filters whose amplitude bandpass characteristic is specified by $p(\omega)$. Note that $p(\omega-\omega_j)-\delta(\omega-\omega_j)$ reduces Equation (3) to the standard optimal non-coherent receiver. Hence, the optimal receiver performs an amplitude spectral analysis and weights the spectral values appropriately. This form of receiver is also optimal for several different oscillator models and criteria as shown by Viterbi, (Reference 5.4-14) and Greenspan and Chesler, (Reference 5.4-15).

The receiver is most easily implemented by band-limiting the incoming signal, sampling, and performing a digital spectral analysis over the T second record. This gives spectral samples spaced at 1/T Hz, the maximum density for independent frequency samples for a T second record of white noise. Thus, in some sense, all the information in the signal waveform is embodied in these frequency samples. Under these conditions Equation (3) becomes a weighted summation.

Thus, the desired receiver should obtain a filtered amplitude spectrum and determine the symbol sent by finding the largest of M decision variables. It would be desirable to have the system performance relatively insensitive to actual oscillator frequency spectra and phase processes since exact determination of these

oscillator characteristics is quite difficult. In order to do this it will be necessary to consider receivers which, if an exact frequency uncertainty model existed would most likely be suboptimal. An example of a good receiver is one employing a rectangular band pass filter. The bandwidth of the filter must be large enough to ensure that most of the time most of the signal energy will be contained in the pass band. For example, if $p(\omega)$ were gaussian with mean zero and standard deviation 0.23Hz (corresponding to a short term oscillator stability of 1:10¹⁰ at 2.3 GHz) then a bandwidth of 1.5 Hz (\pm 0.75Hz) would give a probability of less than 2.5 x 10^{-3} that the signal energy is outside the filter. However, if the true center frequency can be offset as much as 0.2 Hz, then this probability increases to 8 x 10^{-3} .

A second desired operation for this receiver is the ability to track the center frequency of a slowly drifting tone spectrum. It appears at the moment that the only available information on the drift rate is long-term frequency stabilities of the basic oscillators and estimates of maximum drift rate due to uncompensated doppler. Hence an AFC (Automatic Frequency Control) loop must be capable of following the long-term drifts of the system without catastrophically increasing the required bandwidth of the band pass filters. It is precisely the unknown and unpredictable nature of the AFC tracking errors that requires the receiver to be insensitive to the actual signal energy distribution in the decision bandwidth. Because of the "large" phase variations and the small signal powers, phase-lock AFC's will not operate satisfactorily. The AFC's considered here are effectively based on the output of frequency rather than phase information. This information can be obtained using conventional (digital, analog) filters on the outputs of a spectral analysis program. The former is best when there is no spectral analysis performed while the latter appears to be best when a spectrum is obtained.

Since there is a possibility that the receiver will go out of lock, there should be some procedure to indicate loss of frequency lock and to initiate reacquisition. This can be done in two ways. The first procedure demodulates the known sync tone and counts errors. It decides that loss of lock has occurred if there are more than three errors in four successive sync symbols. A second, but more complex procedure, filters the value of the decided decision variable z and states loss of lock has occurred when the filtered output drops below a specified value. Finally, the receiver is required to initially acquire the sync tone frequency and to obtain chip sync. Several approaches are considered for both.

5.4.3.4.2 <u>Design Approaches and Significant Characteristics</u> - Two major configurations for the desired receiver operation were considered. The first is called the "Comb-Filter Receiver" and is characterized by a bank of bandpass filters, each tuned to a single MFSK tone. These are followed by squarers and integrators which are sampled and dumped every T seconds. The tone corresponding to the maximum of the M outputs is that considered sent. The AFC network consists of two stagger-tuned filters whose output difference is filtered and used as an error signal for the VCO. The AFC network must operate on a periodically available sync tone in order to obtain sufficient loop signal-to-noise ratio.

The second major configuration is called a "Spectral Analysis Receiver." This receiver performs a spectral analysis on a T-second length of data and uses the subsequent spectral information to operate a novel AFC loop and loss-of-lock indicator. Except for the analog comb-filter receiver, the systems considered are all digital.

- o Comb-Filter Receiver The comb-filter receiver can be realized with either analog or digital elements. The analog and digital mechanization of the receiver is shown in Figure 5.4-18.

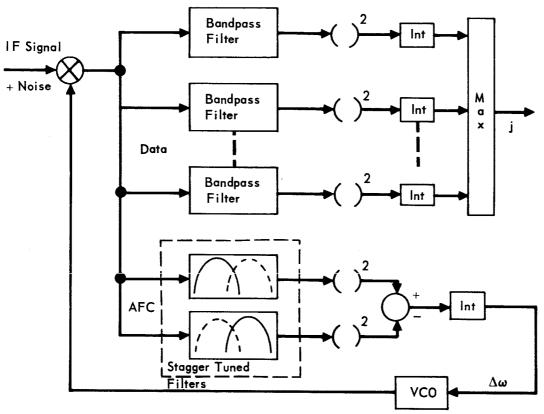
 These two configurations were analyzed only in sufficient detail to determine that: (1) their implementation would be quite complex, (2) the analog comb contains several difficult hardware design problems which must be solved, (3) the digital comb filter could indeed be designed with state-of-the-art equipment but when an adequate system was assembled it represented a large amount of hardware. The digital comb filter can be implemented on a computer. If this is done, it is preferable to implement a spectral analysis receiver as discussed below. The various characteristics of the comb filter receivers
- o <u>Spectral Analysis Receiver</u> This receiver accomplishes the data detection operations by performing a spectral analysis on each of the incoming channel symbols. Block diagrams of two spectral analysis receiver configurations are shown in Figure 5.4-19. The autocorrelation receiver obtains the energy spectrum by finding the autocorrelation function of the sampled incoming waveform and then performing a Fourier transform, usually by an appropriate matrix multiplication. The fast Fourier receiver obtains a periodogram of the sampled incoming waveform directly using a "fast Fourier transform."

 Both systems employ special procedures to reduce the sampling rate required at the detector. Since the autocorrelation receiver does not normally

are discussed in detail in Reference 5.4-16.

COMB FILTER RECEIVER CONFIGURATIONS

a) ANALOG COMB FILTER



b) DIGITAL COMB FILTER

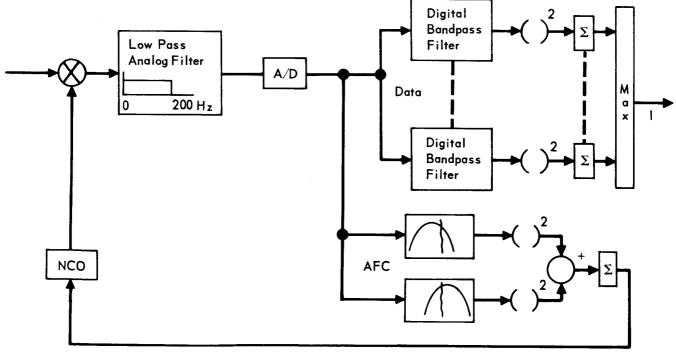
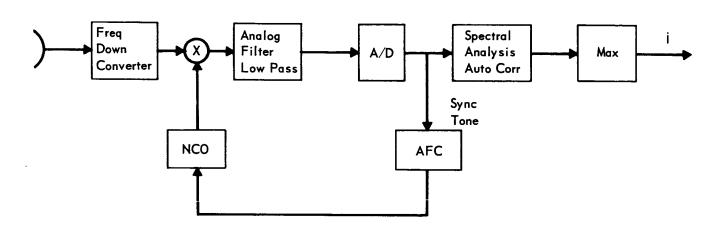


Figure 5.4-18

SPECTRAL ANALYSIS RECEIVER BLOCK DIAGRAMS

Auto Correlation Receiver



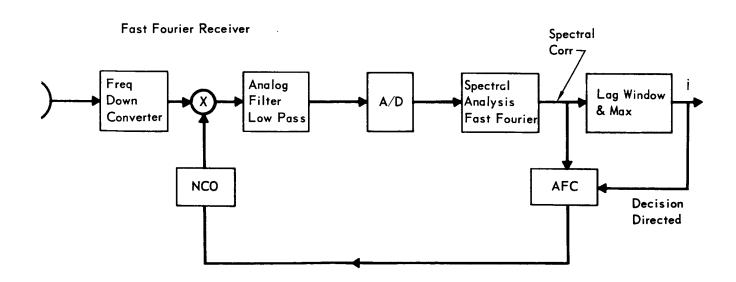


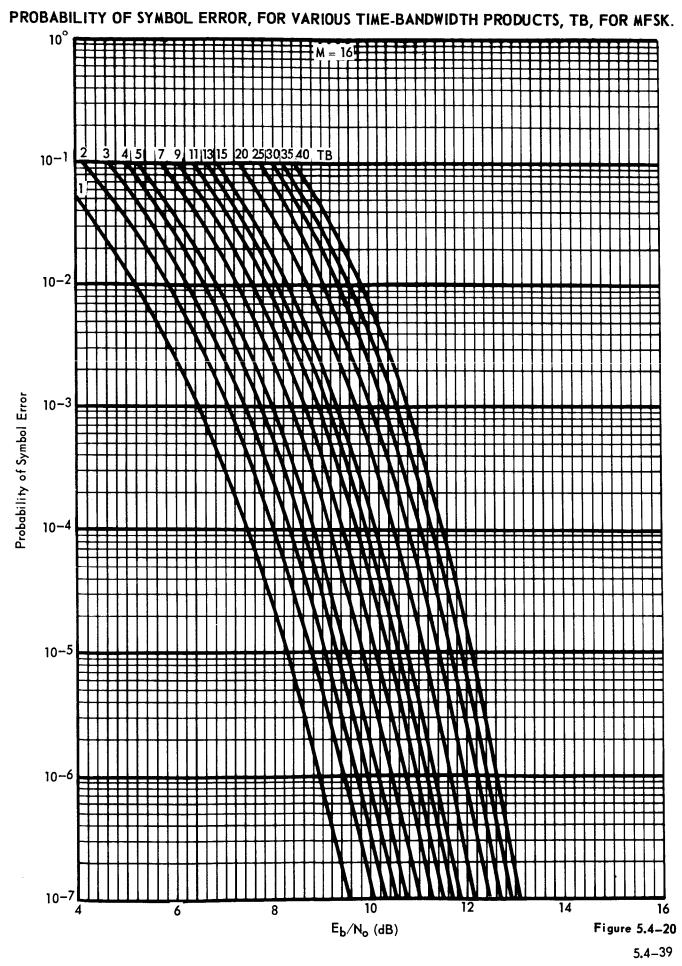
Figure 5.4-19

provide fine structure information, the AFC network required would be like that described previously for the digital-comb-filter receiver. The fast-Fourier-transform receiver provides spectral information spaced 1/T Hz apart. A weighted average of the samples about the nominal center frequencies of the tone form the decision variables and a second weighting is used to form an estimate of the true frequency offset for use in the AFC network. Thus, the AFC network in the fast-Fourier-transform receiver uses readily available information while the AFC network in the autocorrelation receiver must function separately. Although, for both systems, frequency correction may be obtained using analog mixing and a number controlled oscillator (NCO), only for a fast-Fourier receiver can tone separation be specified with east to the nearest 1/T Hz. The autocorrelation receiver tone spacing is specified by the truncation length of the sample autocorrelation function and is not easily changed. Thus for the autocorrelation receiver, the tones must be evenly spaced. The tones may have a spacing greater than $(1/2\tau_{_{\boldsymbol{m}}})$ Hz where $\boldsymbol{\tau}_{m}$ is the cutoff length of the autocorrelation function ($\boldsymbol{\tau}_{m}$ is the maximum separation of samples multiplied together to form autocorrelation) but must have spacings which are multiples of 1/2 $\tau_{_{\boldsymbol{m}}}Hz$. Thus, guard bands between tones are more easily and precisely specified with the fast-Fourier-transform receiver than with the autocorrelation receiver.

For initial frequency acquisition, both receivers will form a spectral analysis over the region of frequency uncertainty. Here again, the efficiency of the fast-Fourier transform gives it the advantage. For initial chip sync, there is really little to choose. Both these receivers can obtain frequency acquisition and chip sync with only minor modification of their computer programs. This is a major advantage over the comb-filter receivers.

5.4.3.4.3 System Performance - For no receiver degradations all systems described have an E_b/N_o vs. signal bandwidth (M = 16) as shown in Figure 5.4-20. The parameter is the time-bandwidth product (TB) and, for the various receivers described, is determined as follows:

- o Comb-filter receiver: B is noise bandwidth of the data filter. Then, TB $\stackrel{\triangle}{=}$ TB.
- o Autocorrelation receiver: τ_m is the truncation point of the autocorrelation function. Then, TB = T/τ_m .
- o Fast-Fourier receiver: TB is the number of values of the spectrum used in the determination of the decision variable.



For each of these receivers, degradation occurs if the signal is not centered in the pass band of the filters. For non-perfect operation of the AFC network, the resulting frequency offset will contribute to degradation of the total system. This degradation depends on the particular configuration under consideration being least for the fast-Fourier receiver.

There is also degradation due to imperfect chip sync. This will be the same for all systems.

5.4.3.4.4 <u>Comparison of Design Approaches</u> - Because of the difficulties involved in the comb filter receiver it will not be discussed further.

A description was given above for the spectral analysis receivers. In order to perform a comparison it is necessary to determine their signal-to-noise degradation characteristics which then define the true input signal to noise ratio required at the receiver input.

Three factors can be defined for the spectral analysis receivers which lead to an increase in power requirements above the theoretical. These are signal power loss due to frequency offset, increased signal power to obtain an acceptable loss of lock probability using the AFC, and increased power to obtain adequate acquisition characteristics. The final part of this section indicates the required (S/N_0) after incorporating all the above losses for the best receiver. We start first by defining the losses.

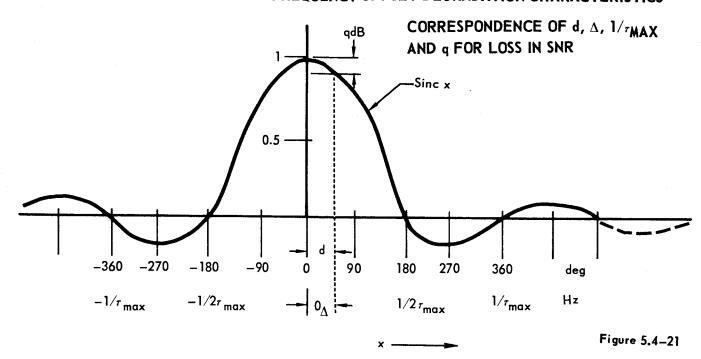
o Loss of Signal to Noise Ratio Due to Frequency Offset

Autocorrelation Receiver - The frequency offset is caused by the imperfect operation of the AFC loop. The autocorrelation receiver obtains the autocorrelation function of the T second sample. The autocorrelation function is truncated at τ_m and then inverted to form the spectrum. The resulting spectrum will have frequency samples spaced at 1/2 τ_m Hz. Assuming the input to be a sinusoid, an estimate of the signal energy loss in terms of frequency offset and τ_m has been derived. The relationships thru the sinc function (which is the spectral window characteristic for the autocorrelation receiver) of the several parameters of interest are shown in Figure 5.4-21. These parameters are:

- d argument of sinc function, degrees
- Δ frequency offset, Hz
- T_{m} truncation point of autocorrelation function
- q reduction in signal power (or signal to noise ratio).

Figure 5.4-22 also tabulates the loss for Δ = 0.75Hz for various values of TB product.

AUTOCORRELATION RECEIVER FREQUENCY OFFSET DEGRADATION CHARACTERISTICS



AUTOCORRELATION RECEIVER FREQUENCY OFFSET DEGRADATION CHARACTERISTICS

SIGNAL LOSS q dB	EQUIV deg d	$\frac{1}{\Delta T_{\text{max}}} = \frac{360}{d}$	TB PROD $ \frac{360}{d} \Delta.T $ $ \Delta = .75, $ $ T = 4 $	ADDITIONAL LOSS OVER MIN. TB = 6 $P_e = 10^{-3}$, M = 16	T OTAL LOSS dB
.1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8	21.6 30.0 36.5 42.0 47.1 51.5 55.5 59.25 62.5 65.75 68.75 71.75 74.5 77.15 79.75	16.7 12 9.87 8.57 7.64 7.0 6.59 6.08 5.76 5.475 5.23 5.02 4.83 4.67 4.52	51 36 29.5 25.6 23 21 19.8 18.2 17.3 16.4 15.7 15 14.5 14.5	2.8 2.4 2.1+ 1.9 1.8- 1.65 1.55 1.47 1.4 1.3 1.2 1.13 1.1	2.9 2.6 2.4 2.3 2.3 2.25 2.27 2.3 2.3 2.3 2.3 2.4 2.45 2.47
2.0	90.5	3.98	12	0.9	2.9

Figure 5.4-22

5.4-41

Fast Fourier Receiver - An equivalent passband for this receiver is sketched in Figure 5.4-23. It can be seen that the worst case occurs when the signal is in the "dip" nearest the edge of the passband. For Δ = 0.75 Hz, a time bandwidth product of 7 (6 minimum) is required. The total minimum signal energy is found by adding up the signals in the 7 incremental passbands. Thus we get, for a signal midway between the "+2" and "+3" cells the following totals:

Example	Cell	Energy (sinc ² X)	X°	
	+3	.405285	90	
	+2	.405295	90	
	+1	.045032	270	
	0	.016211	450	
	-1	.008271	630	
	-2	.005004	810	
	-3	.003349	990	
		.888437		0.51 dB

Additional Loss (For TB=7 vs. TB=6) 0.17 dB 0.68 dB

Hence the total loss for the fast fourier transform receiver is less than 0.7 dB over the "best" receiver and less than 0.51 dB when compared to an input with no offset.

o Increase in Signal Power to Obtain Acceptable Probability of Loss of Lock - For low signal to noise ratios, the AFC network is more sensitive to noise than the data detection. To justify the (S/N_O) vs. data rate table given in Figure 5.4-24 a brief description of the novel AFC employed in the fast-Fourier-transform receiver will now be presented. The analysis for the digital filter AFC employed by the autocorrelation receiver is identical except for the frequency estimate.

Exact Equivalent Model - The exact equivalent model of the AFC network is given in Figure 5.4-25. The system obtains a noisy estimate of the frequency difference, $\Delta \hat{\omega}$ (n), of the true frequency difference, $\Delta \hat{\omega}$ (n), using a noisy measuring device which is described in more detail in Figure 5.4-25. The noisy estimate, $\Delta \hat{\omega}$ (n), is filtered with a sample data filter whose z-transform is F(z). The final delay, z⁻¹, indicates the natural delay in the system. As is usual in these cases, neither ω (n) nor $\Delta \omega$ (n) are available to us.

PLOT OF EFFECTIVE FILTER PASSBAND FOR FAST FOURIER TRANSFORM RECEIVER

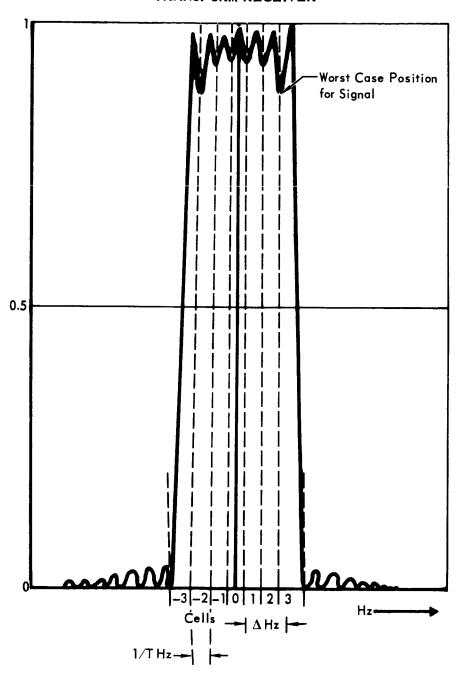
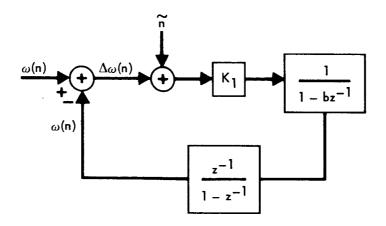


Figure 5.4-23

SECOND-ORDER AFC LOOP



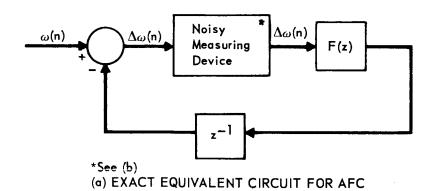
SIGNAL TO NOISE RATIO REQUIREMENTS VS. DATA RATE FOR ADEQUATE AFC OPERATION

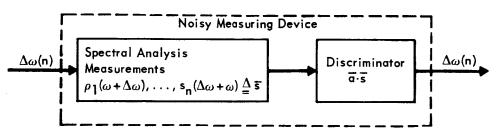
DATA RATE Bits/sec	CHIP LENGTH T sec	TIME BANDWIDTH PRODUCT (2v + 1)	STEADY STATE ERROR, E _{SS} Hz	SYSTEM PARAMETERS	REQUIRED Na	REQUIRED S/No.,dB
0.5	8	13	0.2	$\begin{array}{l} {\rm b = 0.3} \\ {\rm k_1 = 0.28} \\ {\sigma_{\Delta}}^2 = 0.2241 \; {\rm Na} \end{array}$	≤ 0.054	9.7
0.6	6.66	11	0.2	$\begin{array}{l} b = 0.3 \\ k_1 = 0.2115 \\ \sigma_{\Delta}^{\ \ 2} = 0.1932 \ \text{Na} \end{array}$	≤ 0.0626	8.54
0.8	5	9	0.2	$\begin{array}{l} b = 0.5 \\ k_1 = 0.125 \\ \sigma_{\Delta}^{\ 2} = 0.1304 \ \text{Na} \end{array}$	≤ 0.0928	6.25
1.0	4	7	0.2	$b = 0.6$ $k_1 = 0.08$ $\sigma_{\Delta}^{2} = 0.1026 \text{ Na}$	≤ 0.118	4.8

Parameters: h = 0.01 Hz/sec, σ_{ω} = 0.23 Hz System loss of lock probability = 10^{-3}

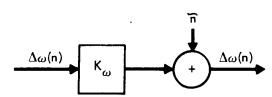
Figure 5.4-24

AFC NETWORKS





(b) DETAILED DESCRIPTION OF NOISY MEASURING DEVICE



(c) APPROXIMATE EQUIVALENT CIRCUIT FOR NOISY MEASURING DEVICE WITH GAIN K AND ZERO-MEAN WHITE GAUSSIAN NOISE $\widetilde{\bf n}$ VARIANCE $\bf N_a$

Figure 5.4-25 also shows the noisy measuring device in more detail. The output of the first box is a set of spectral measurements of the noisy process. These measurements can be considered as a spectral vector which is then dotted with the discriminator vector, \overline{a} , to give the output, $\Delta \hat{\omega}(n)$. This linear operation could be replaced by a nonlinear operation such as the centroid, median, or other measure. Since we are going to make a major approximation next by replacing the system in Figure 5.4-25 with an "equivalent" gain, K, and additive white Gaussian noise with variance N_a as shown in Figure 5.4-25, the exact form of the discriminator can be determined by evaluating the new gain and variances that result.

For the autocorrelation receiver, the noisy measuring device is two staggertuned digital filters which will produce an estimate whose variance is at least as large as the best FET receiver AFC variance. This is the only place where the analyses of these two AFC's differ.

For a discriminator characteristic, a, which produces $\Delta\omega(n)$ as an unbiased estimate of the true frequency difference $\Delta\omega(n)$ it is shown (Reference 5.4-16) that, when the signal frequency is Gaussian with mean zero and a standard deviation σ_{ω} , N_a , the variance of $\Delta\hat{\omega}$, is bounded by

$$N_a \le \frac{1}{\frac{(2ST)^2}{N_o}} - \frac{2V(V+1)(2V+1)}{6} + \frac{4ST}{N_o} \sigma_{\omega}^{2}^{2}$$
 (1)

where $\frac{S}{N_O}$ is the signal to noise density ratio

(2V + 1) is the time bandwidth product and T is chip time.

For typical signal conditions (S/N_O = 5, T = 4, V = 3 (K - 7), (σ_{ω} - 0.23 Hz), then from Equation (1)

$$N_a \le \frac{1}{1600} (28 + 80) = 0.068$$

Dynamics of Second Order AFC Loop - Rather than study a general loop and obtain general results, a specific loop was studied, namely a second-order loop, and specific results obtained. The reasons for studying a second-order loop are that there are only two parameters to vary, the loop remains stable for all loop gains, and the loop tracks a constant Doppler-rate with a finite steady-state error. The loop parameters were designed based on a tradeoff between closed-loop frequency error variance and steady-state (noiseless) tracking error. The loop studied is shown in Figure 5.4-24.

The loop has zero-mean additive white Gaussian noise, \tilde{n} , with variance N_a , loop gain K_1 , filter bandwidth parameter b, and a perfect summer (integrator) with a delay for realizability. The transfer function for this loop with W(z), N(z), and $\Delta W(z)$ being the z transforms of $\omega(n)$, $\tilde{n}(n)$, and $\Delta \omega(n)$, respectively, is

$$\Delta W(z) = W(z) \frac{1}{1 + F(z)} - N(z) \frac{F(z)}{1 + F(z)}$$
where
$$F(z) = \frac{K_1 z^{-1}}{(1 - bz^{-1})(1 - z^{-1})}$$
(2)

Now, if $W(z) = (hz^{-1})/(1-z^{-1})^2$ corresponding to a Doppler rate of (h/T) Hz/second, then the steady-state error, E_{ss} , using the final value theorem is

$$E_{SS} = \frac{\lim_{z \to 1} W(z) \frac{1 - z^{-1}}{1 + F(z)} = \frac{h(1 - b)}{K_1}, \ b < 1$$
 (3)

The variance of the frequency estimate, $\hat{\omega}$, defined to be $\sigma_{\Lambda}^{\ 2}$ is found to be

$$\sigma_{\Delta}^{2} = N_{a} \left[\frac{K_{1}}{1 - b} \right] \frac{1 + b}{2(1 + b) - K_{1}}$$
 (4)

For reasonable steady state errors, it is possible to obtain the transient response of the loop to various Doppler rates for diverse b and K. The loop gain K, is chosen to be as small as possible in order to minimize $\sigma_{\Delta}^{\ 2}$ in Equation (4) but large enough to be consistent with the steady state error of Equation (3). The filter bandwidth parameter, b, is chosen to give a slight overshoot for the given Doppler rate.

As an example we have:

 $E_{SS} \leq 0.1 Hz$

 $h \le 0.04$ Hz/chip (this is equivalent to 0.01 Hz/sec)

 $N_a = 0.068$

Choose b = 0.3

Thus using (3) $K_{\frac{1}{2}} = 0.28$

and using (4) $\sigma_{\Delta}^{2} = (N_a)(0.2241) = 0.0152$

and hence a standard deviation of $\sigma_{\Lambda} = 0.123$

Calculation of Probability of Loss of Lock - The probability of no loss of lock is just the probability that $|\Delta\omega| < B/2$ for the total length of the mission. For $\sigma_{\Delta} = 0.12$, $E_{ss} = 0.1$, we have 1.5 Hz implying +5.4, -6.4 standard deviations giving a probability of $|\Delta\omega| > B/2$ of 5 x 10^{-7} . For 7 hours of transmission at

1 bit/sec, M = 16, T = 4, there are 7300 chips and, hence, a loss-of-lock probability of less than 3×10^{-3} for the entire mission.

To determine the (S/N_O) required to operate the system for a mission loss-of-lock probability of about 10^{-3} we need 0.75 Hz (B/2) to be about 5 standard deviations of σ_{Δ} plus the steady state error. Appropriate system parameters are chosen with the help of the plots of loop transient response. Hence, we obtain a required N_a and solve (3) for S/N_O. These requirements are given in Figure 5.4-24 for various data rates.

o <u>Power Requirements Due to Frequency Acquisition and Initial Chip Sync</u>
Because the MFSK receiver is constrained to operate in real time without loss of data, a special acquisition sequence must precede the first datum. If the real time constraint were removed, both frequency acquisition and chip sync could be attempted using the data and then the tape could be run backwards to the beginning with a resultant recovery of all data.

To reduce the complications and increase the efficiency of the initial acquisition, it is proposed that a sync tone be sent continuously for several minutes to obtain frequency followed by known frequency-hopped sequences (e.g., square wave modulated FSK) to obtain chip sync. This procedure is proposed in order to alleviate the loss of SNR due to frequency offset during chip sync or timing offset during frequency acquisition. The acquisition times (frequency and chip sync) sum for low SNR.

Frequency Acquisition - The receiver is required to find the frequency of the sync tone (or any other tone) to within 0.1 Hz. It appears to be reasonably easy to find the sync tone frequency to within the bandwidth of the oscillator but exceptionally time consuming to lock in much closer. For example, frequency resolution of 0.1 Hz requires time records of, at least, 10 seconds.

Any procedure for finding the unknown frequency effectively breaks the frequency uncertainty region into a large number of small cells and tests to determine which cell has the signal. A filter that sweeps continuously over the uncertainty band searches each cell sequentially while the spectral analysis receivers search many cells in parallel.

A major difficulty arises when we wish to determine the center frequency to an accuracy better than the bandwidth of the oscillator. This precision is difficult because the discrimination must be made on the basis of differences in signal energy which are small compared to the total signal energy. Hence, we must look for a long time in order to get decision variables which differ enough to make a reliable decision.

A second problem that arises is due to the frequency drift of the system and uncompensated Doppler. This can result in drifts as high as 0.01 Hz/sec which, over 10 minutes, is about 6 Hz. Hence, the final fine-frequency determination has to be done quickly and the AFC initialized for tracking. This leads one to consider two-level searches. The specific two-level search recommended for the fast-Fourier-transform receiver has the advantage of not requiring any hardware MDE (a software program is required).

The procedure looks at 40 successive one-second samples, performs a spectral analysis of each, accumulates the totals and finds and saves the maximum. The NCO is then increased by 200 Hz and the sequence repeated. Thus, to cover a 4 kHz bandwidth, the sequence has to be repeated 20 times. In order to obtain the correct 1 Hz interval with a probability of error of 10^{-7} , a signal-to-noise ration, S/N_O , of 4 dB is required. For a nominal S/N_O of 7 dB, this is a 3 dB margin. For the total of 4 kHz uncertainty, frequency acquisition takes $20 \times 40 = 800$ seconds or 13.3 minutes. Unfortunately, during this time the frequency could have drifted 8 Hz and, so, is probably not where the maximum indicates it to be. After this initial 13.3 minutes, the NCO is then set at the indicated center frequency less 100 Hz.

The next 20 seconds of data are divided into five, 4-second records and a spectral analysis is made on each. The maximum of the 160 values in a 40 Hz frequency interval centered around the nominal center frequency given above results in the true center frequency of the spectrum to within 1/4 Hz with a probability of error of 10^{-7} and a 3 dB margin. Note that during this last 20 seconds the drift should be less than 0.2 Hz. The AFC is now initialized. Thus, the total frequency acquisition time is about 14 minutes.

Increased Power to Provide Adequate Chip Sync - In contrast to frequency acquisition described above, the signal powers available are not adequate to provide chip sync in a reasonable length of time. In order to obtain chip sync it is necessary to take a rather appreciable loss in (S/N_O) .

Assuming Gaussian distributions $^{\rm l}$ for the decision variables, a relationship involving an upper bound on the chip sync search time, $t_{\rm u}$, k and the signal degradation, a, has been derived. It is

$$t_{u} = \frac{2b_{m}}{a^{2}} \qquad \left[\frac{\frac{k}{T} + 2(1-a) \frac{S}{N_{0}}}{\left(\frac{S^{2}}{N_{0}}\right)^{2}} \right]$$
 (5)

Where we define

 t_u - upper bound on time to synchronization

 b_m - signal energy required to differentiate between one signal of power S and (m - 1) signals of power (1 - a)S with a probability of error defined by S/N_O and a.

a - fractional loss of power, i.e., $\alpha = 10 \log a$, where $\alpha = power loss in dB$

k - time bandwidth product

T - chip length, seconds

 S/N_0 - signal power to noise density ratio

Several examples are given in Figure 5.4-26 for $Pr(E) = 10^{-3}$. The third column is obtained by assuming the dedicated use of an SDS 930 which should be capable of about four spectral analyses every T seconds. A 0.5 dB loss requires ten spectral analyses so that the basic time is multiplied by three whereas 0.58 dB loss only requires 8 spectral analyses and hence a multiplication of the basic time by two.

o <u>Signal Power'Required for Various Data Rates Using MFSK</u> - The preceding discussion has shown that in every case the fast-Fourier-transform receiver is superior or equal to the autocorrelation receiver. The discussion henceforth treats only the fast-Fourier-transform receiver.

To determine the total required ($S/N_{\rm O}$) for various data rates, we collect the cases of the previous sections:

Data Rate (Bits/Sec)	for Data	Freq.Offset Degradation (dB)	Req'd Data S/N _o (dB)	Req'd AFC S/N _o (dB)	Chip Sync Loss (dB)	Total Req'd S/N _o (dB)
0.5	5.1	0.5	5.6	9.7	0.58	10.3
0.6	5.65	0.5	6.15	8.54	0.58	9.12
0.8	6.6	0.5	7.1	6.25	0.58	7.7
1.0	7.3	0.5	7.8	4.8	0.58	8.4

Required (S/N_0) for Adequate AFC

Acquisition and Data Detection Characteristics for M = 16

This is a reasonable assumption because the time bandwidth products of the decision variables are several hundred even in the best case.

CHIP SYNC DEGRADATION

R bps	S/No dB	TIME FOR BASIC SYNC, t _u min	TOTAL TIME,	LOSS, dB
0.5	9.7	10.4	~ 31	0.5
0.6	8.54	11.6	~ 34.8	0.5
0.8	7.1	16.4	~ 48	0.5
1.0	7.8	13.68	~ 41	0.5
0.5	9.7	7.8	15.6	0.58
0.6	8.54	8.6	17.2	0.58
0.8	7.1	12.2	24.4	0.58
1.0	7.8	10.2	20.2	0.58
1.0	7.0		> 6 hr	0.1

If we assume our minimum required data rate to be 0.5 bps, the preceding results show that if we satisfy the AFC requirements we can increase the data rate for an increase in power. We can determine an optimum data rate as follows: First determine S/N_0 versus data rate required to provide an acceptable probability of loss of lock (say 10^{-3} for the mission). Secondly determine S/N_0 versus data rate required to provide an acceptable bit error rate (say 5×10^{-3}). Where these two lines intersect is defined as data rate requiring minimum power to satisfy all requirements. This is shown to be 0.75 bps in Figure 5.4-27.

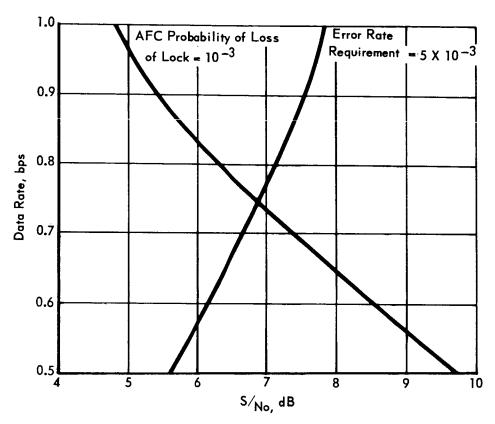
5.4.3.4.5 <u>Recommended Receiver Configuration</u> - A detailed comparison matrix is presented in Figure 5.4-28 for the various receiver configurations described in the preceding discussion. In Figure 5.4-29, a summary comparison matrix is presented to highlight our choice.

Two implementations are listed for the first-Fourier spectral analysis receiver. Configuration A (Design 4) utilizes a special purpose fast Fourier transform "black box" prior to entering the computer. Configuration B (Design 5) performs the fast Fourier operation within the computer.

The receiver recommended is Configuration B (Design 5). All the components required are readily available and of moderate cost. This receiver is the most efficient and versatile of any receiver considered. It is however, a little slower than Configuration A (Design 4) during initial frequency acquisition. However, the possible difficulty of obtaining an A/D converter to provide 12-16 bits conversion accuracy for analog signals band limited to only 4 kHz (or even 2 kHz) and the need to develop a fast Fourier transform unit, both required for Configuration A, lead us to decide in favor of Configuration B.

¹Reference 5.4-16 shows that 12-16 bits conversion accuracy are required for Configuration A whereas 5 bits is adequate for Configuration B.

DETERMINATION OF OPTIMUM DATA RATE



DETAILED TRADE STUDY - LOW DATA RATE MESK RECEIVER IMPLEMENTATION

DETAILED TRADE STU	DY - LOW DATA RATE MFSK	RECEIVER IMPLEMENTATION	
FUNCTIONAL & TECHNICAL	1.0 ANALOG COMB FILTER	2.0 DIGITAL COMB FILTER	MAT 3.0 SPE
DESIGN REQUIREMENTS	RECEIVER	RECEIVER	AU RE
Trades — Detail 1.0 Versatility 1.1 Spectral filter shaping	– Difficult	– Easier	– Diffic
1.2 Sync tone, periodic or continuous	- Impossible	– Easy	– Easy
1.3 Separate acquisition circuit required	– Yes	– Yes	– No (s
1.4 Fine freq. information for AFC	- None	– No	– No
1.5 Variability of tone spacings	– Very difficult	Easy	– Diffic
1.6 Ease of filter dumping	- Difficult	– Easy	– Easy
2.0 AFC Operation 2.1 Discriminator versatility	- Negligible	— Minimal	— Minim
2.2 Loop Filter Implementation	- Difficult	– Easy	– Easy
3.0 Initial Acquisition 3.1 Amount of parallel processing	– Virtually none	- Easier than in 1 to get more	– Moder
3.2 Ease of implementing multilevel searches	Very difficult	— Difficult	– Moder
4.0 Degradations 4.1 Signal loss due freq. offset	?	?	- Highe
4.2 Receiver VCO Instabilities	– Can lead to even more degradation	- No VCO	- No V(
4.3 Sampling	— Not applicable (N.A.)	— Possibly large due to high rate	Possi
4.4 Quantization			
 Data Parameters 	– N.A.	1. High 2. High	1. Low 2. Mode
3. Operations		3. Very high	2. Mode 3. Mode
4.5 Chip Synchronization without clock timing	— Very difficult	— Slow (No parallel processing)	– Moder speed
4.6 A/D Converter	– N.A.	– N.A.	- Least
		L	

Figure 5.4-28

5.4-54-1

1	
OCORRELATION EIVER FOURIER RCVR CONFIGURATION A FOURIER RCVR CONFIGURATION B SELECTION It - Very easy - Very easy (5-4) - 2-3- - Easy - Easy (2,3,4,5) - 1 itware only) - No (software only) (3,4,5) - (2,1) - Yes - Yes (4,5) -2-3-1 It - Very easy (to 1/T Hz) - Very easy (to 1/T Hz) (4,5) -2-3- - Easy - Easy (2,3,4,5) - 1	
- Easy - Easy (2,3,4,5) - 1 - No (software only) - No (software only) (3,4,5) - (2,1) - Yes - Yes (4,5) -2-3-1 - Very easy (to 1/T Hz) - Very easy (to 1/T Hz) (4,5) - 2-3- - Easy - Easy (2,3,4,5) - 1	
itware only) — No (software only) — No (software only) — Yes — Yes — Yes — Yes — Very easy (to 1/T Hz) — Very easy (to 1/T Hz) — Easy — Easy — Easy — Easy — (2,3,4,5) — 1	
- Yes - Yes (4,5) -2-3-1 It - Very easy (to 1/T Hz) - Very easy (to 1/T Hz) (4,5) - 2-3-1 - Easy - Easy (2,3,4,5) - 1	,
The image of the	1
- Easy - Easy (2,3,4,5) - 1	
- Good - Good (4,5) - (2,5)	
	- 1
- Easy - Easy (2,3,4,5) - 1	
te - Most - Considerable 4-5-3-2-1	
tely difficult — Easy — Easy (4,5) — 3—2—	
than 4 or 5 — Least — Least (4,5) —3	
O — No VCO — No VCO Only analog shas degradated due to VCO	-
ly large due to high rate — Possibly large due to high rate — Lowest 5 — (2,3,4) T degradation i assumed neglin worst case	igible
1. Very high 2. Very high 2. Very high 3. Very high 3. Very high 3. Very high	
te (Depends on exact — Fastest — Fast 4— (5,3)—2— (Placement of questionable)	
stringent - Most stringent - Stringent 3-5-4	3

SUMMARY TRADE STUDY - LOW DATA RATE MFSK RECEIVER IMPLEMENTATION

			MATRIX
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS	1.0 ANALOG COMB FILTER RECEIVER	2.0 DIGITAL COM FILTER RECEIVER	3.0 SPECTRAL AUTOCORR RECEIVER
Demodulates M tones for data rates from 0.5 to 1.0 bps. Performs initial frequency acquisition and chip sync & tracks a drifting signal using an AFC.	Uses M analog tone filters, squares output, integrates samples & dumps. Compares to find largest of M. AFC from two stagger-tuned filters.	Same as 1.0 but entirely digital.	Performs digital by finding trunc tion & inverting criminator. Initi overlapping spe
Trades-General 1.0 Versatility	- Least - Filters are unstable & difficult to shape - Continuous sync tone only - Difficult to change M	- Moderate - Continuous or periodic sync tone - Spectral shaping difficult - Difficult to change M	— Moderate — Spectral shap
2.0 AFC Operation	- Separate special circuit - Continuous sync tone only	- Uses only two spectral measurements for freq. estimate - Periodic or continuous sync tone - Cannot be decision-directed without large increase in complexity	- Same commer
3.0 Initial Acquisition	 Slow Must sweep filters & note max. (difficult) Need more filters for reasonable acquisition time 	- Slow - Even more difficult to sweep than No. 1 - Need more filters	 Moderate Spectral deta Two level so when freq.
4.0 Degradations	 Large due to filters instabilities & poor AFC operation No detailed power losses 	 – Moderate – Moderately sensitive to freq. offset. – No detailed power losses 	– Moderately– Sensitive to– Least sensi
5.0 Signal Power Requirements	— High due to known instabilities	- Reasonáble	 Moderately sensitivity
6.0 Complexity	 Very Special analog control for filters Special acquisition circuit 	 Very (Simpler than 1) Special purpose implementation of filters and AFC 	 Moderate Special pury (Commercial purse Special purse AFC

Figure 5.4-29

5.4-55-/

OF DESIGN APPR			
ANALYSIS ELATION	4.0 SPECTRAL ANALYSIS FAST FOURIER RCVR CONFIGURATION A	5.0 SPECTRAL ANALYSIS FAST FOURIER RCVR CONFIGURATION B	SELECTION
spectral analysis ited autocorrela- digital filter dis- I acquisition by tra.	Performs digital spectral analysis by fast fourier trans. AFC uses spectral measurements for discriminator. Initial acquisition by overlapping spectra. Uses special-purpose Fast fourier transform black box on on 2KHz freq. BW.	As in 4.0, but uses general purpose computer for fast fourier transform signal is mixed with an AFC controlled NCO and filtered to 200hz BW.	No. 5
ing difficult	Good	Good	(4,5) - 3-2-1
nts as 2.0	- Uses detailed spectral information - Can be decision-directed - Continuous or periodic sync tone	— Same comments as 4.0	(4,5) - (2-3) - 1
il difficult to obtain earches difficult drifting	Very fast (2KHz BW)Multilevel searches easySpectral detail easy	Fast (200 Hz BW)Multilevel searches easySpectral detail easy	4-5-3-2-1
orge freq. offset ive to quantization	— Least — Only due to freq. offset	LeastOnly due to freq. offset	(4,5) - 2-3-1
igh due to AFC	– Least	– Least	(5,4) - 2-3-1
ose Autocorrelator Ily available) ose computer ose digital filter	 Moderate Special purpose Fast Fourier Transform Small general purpose computer Very good A/D converter 	 Least General purpose computer NCO and L.O. for input mixing 200 Hz analog filter (sample) . 	5-4-3-2-1

5.4.4 <u>Backup Links</u> - A backup mode for the high data rate link is an alternate mode of operation which transmits all or a portion of the high rate link information (3 x 10⁷ bits per day) should the high rate link fail. A backup mode of operation is desirable if the cost (in pounds, watts, complexity etc.) is not too great. It is the purpose of this section to describe possible modifications or additions to the baseline system for the purpose of providing a backup link.
5.4.4.1 <u>Study Approach</u> - To compare the capabilities of the various backup approaches, four data requirement groupings were postulated as shown in Figures 5.4-30, -31, and -32. These groupings represent Low Rate Science (LRS) 12,000 bits; Engineering Data (ED), 65 K bits; Intermediate Rate Science (IRS), 416 K bits; and High Rate Science (HRS), 600 K bits, samples of experimental data strictly to demonstrate what might be returned by a specific daily data rate.

The five candidate backup approaches described in Paragraph 5.4.4.4 fall into two categories - those which will backup only the low rate and high rate science and those which will backup low rate and high rate science and TV data. The first category includes two S-band direct links, and the second includes three UHF relay links. Since a comparison of the two categories is desirable, the same design requirements are considered for comparison of links in the same category. 5.4.4.2 Summary - These comparisons show the UHF relay-2 and S-band Direct-2 are preferred. The UHF link is preferred because all data including TV is backed up for only a small increase in weight on the SL and FSC (See Figure 5.4-33). The S-band link is preferred because all the low rate and all the high rate science data is backed up (See Figure 5.4-34). Note that the MFSK low rate link used in the preferred design is incapable of providing backup for any data grouping besides the LRS.

5.4.4.3 <u>System Constraints</u> - The constraints assumed for each type of system are listed below:

- S-Band: Maximum power output = 50 watt TWT
 - ° Antenna gain (additional antenna) < 6 dB
 - Automatic turn-on of backup mode

UHF Relay: Assumed orbit 1,000 x 20,000 kilometers (altitude)

- Maximum power output = 40 watts solid state
- o Antenna gain (additional antenna) = 5 db (2 dB minimum)
- ° Transmission distance = 20,000 km
- Do not use CB or ESP transmitter, automatic turn-on of backup mode

LOW RATE SCIENCE

	TOTAL DATA BITS
I. Turn on and minimum checkout and verification 13 bits/instrument x 14 instruments	182
2. Minimum operation of each instrument	
Atmosphere Measurement every 6 hours (6 meas)	
Pressure: 7 bits/meas x 6 meas	42
Temperature: 7 bits/meas x 6 meas	42
Wind Velocity: 3 vel x 8 bit/vel x 6 meas	144
Humidity: 7 bit/meas x 6 meas	42
Range: 1 bit/meas x 6 meas	6
Subsurface Probe Measurements every 6 hours (6 meas)	
Temperature: 9 temps/meas x 7 bits/temp x 6 meas	378
Ref Jct Temp: 7 bits/meas x 6 meas	42
Moisture: 5 moisture/meas x 7 bits/temp moist. x 6 meas	210
Range: 5 bits/meas x 6 meas	30
Image System Checkout	
100 elements x 6 bits/element	600
Three Life Detectors	
1) Growth	
3 chambers x 95 bit/3 chambers x 3 subframes/meas x 5 meas	1425
2) Metabolism	
8 chambers x 3 meas/chamber x 46 bits/meas	1104
4 In situ Metabolism detectors	
4 detectors x 3 meas/detector x 24 bits/meas	288
3) Third Life detector	
3 measurements x 300 bits/meas	
Gas Chromatograph — 1 spectrum (50% resolution)	
Column temp: 8 bits/meas x 10 meas	
Oven temp: 1 meas/spectrum x 8 bits/meas	8
Alpha Spectrometer 1 spectrum (a & p) (50% resolution)	2048
1 Head Temp x 6 bits/meas x 4 meas	24
1 Electronic Temp. x 6 bits/meas x 4 meas	
2 Voltages: 12 bits/meas x 4 meas	48
Spectro-Radiometer 1 spectrum	2000
	12,167
10.177	-•

The total data of 12,167 bits require a transmission rate of: $\frac{12,167}{3600 \times 6 \times 0.8} = 0.7$ bits/sec for a 6 hr transmission time and 80% format efficiency.

INTERMEDIATE RATE SCIENCE

	INTERMEDIATE RATE SCIENCE	
		TOTAL DATA BITS
1. Turn-on checkout	t and verification	
	nt x 14 instruments	546
2. Science Data		
Atmospheric Date		700
Pressure	7 bits/meas x 4 meas/hr x 26 hr 7 bits/meas x 60 meas/hr x 4 hrs (sunrise and sunset)	728 1680
Temperature	2 sensors x 7 bits/meas x 4 meas/hr x 26 hrs	1456
, opo. 2.0.	2 sensors x 7 bits/meas x 60 meas/hr x 4 hrs (sunrise and sunset)	3360
Wind	6 sensors x 8 bits/sensor x 6 (1 meas./10 sec for 1 min) x 4 (1 min operation/15 min) x 26 hr	29,952
(Sunrise & Sunset)	6 sensors x 8 bits/sensor x 60 meas/hr(wind vel every min)x4hr 2 sensors x 7 bits/meas x 4 meas/hr x 26 hr	11,520
Humidity Subsurface Probe	2 sensor x 7 bits/meas x 60 meas/hr x 4 hr (sunrise and sunset)	3360
Temperature	10 sensors x 7 bits/sensor x 4 meas/hr x 26 hrs	7 280
(Sunrise & Sunset)	10 sensors x 7 bits/sensor x 60 meas/hr x 4 hrs	16800
Moisture	5 sensors x 7 bits/sensor x 4 meas/hr x 26 hr 5 sensors x 7 bits/sensor x 60 meas/hr x 4 hr	3640 8400
(Sunrise & Sunset)	5 sensors x / bits/sensor x ou meds/iii x 4 iii	·
Range Penetration De	5 bits/measurement x 344 measurements	1720
Penetration De	7 bits/0.01 sec x 2 sec	1400
Three Life Detector	s	
1) Growth	27.1	22 400
temperatures, o	0 bits/chamber/meas x 12 meas/hr x 27 hr amplifiers mode and frame sync pulse monitoring	32,400 9,840
2) Metabolism 32 chambers x	1 meas/32 min x 12 hr x 60 min x 38 bits/meas	27,360
1 temp/15 min.	x 12 hr x 60 min/hr x 8 bits/temp	384
4 bits, 1 bit te	- 11 bits β count, 11 bits prev. β count, pH 8 bits, det head ident. st/control count > 2, 1 bit anti met. status, 1 bit illum cham 1-14, 1 bit illum cham 15.)	
(24 bits/meas	les x 24 bits/meas x 4 meas/hr x 5 hr = 11 bits β count, 2 bits in situ capsule identification, 1 bit for test/er count > 1. 1 bit for test/control chamber > 2, 1 bit for anti-metabo-	1920
	ector (not yet defined)	30,000
Gas Chromatograph	200 1 11 1/1 11	130,000
26 spectra x 50 (26 spectra = 8 face gas samp	100 bits/spectrum soil samples x 2 pyro temp. + 4 reference samples + 6 subsur-	130,000
	100 bits/spectrum	18,700
(17 spectra = 7	surf. atm + 8 subsurf. gas + 2 reference)	•
	8 bits/meas x 3 meas/spect. x 16 spectra 8 bits/meas x 1 meas/spect x 12 spectra	384 960
Alpha Spectrometer		10.000
6 α spectra x 2	56 channels/spectrum x 8 bits total count/channel 56 channels/spectrum x 8 bits total count/channel	12,288 12,288
	(2 head + 2 elect) x 6 bits/temp x 1 meas/hr x 30 hr	720
4 voltages x 6	bits/voltage x 1 meas/hr x 30 hr	720
	rate: 10 detectors x 6 bits/detector x 1 meas/2 hr x 30 hr on x 1 bit/position x 1 sample/hr x 30 hr	900 300
Spectro-Radiometer		40.000
20 spectra x 200	00 bits/spectrum ors x 4 meas/hr x 12 hrs (daylight) x 8 bits/meas	40,000 1920
	x 4 meas/hr x 12 hrs (daylight) x 8 bits/meas	1152
	bit/meas × 1 meas/hr × 30 hrs × 1 sensor	240 240
Sample Processor S		
	amples × 7 bits/sample Total non-imaging data	21 416,035
lmaging data	- -	
	elements x 200 lines x 6 bits/element Total data	480,000 896,035
The total data of 89	96,035 bits requires a rate of	
$\frac{896,035}{3600\times6\times0.8} = 52 \text{ bit}$	s/sec for a 6 hour transmission and 80% format efficiency	

ENGINEERING DATA, HIGH RATE SCIENCE AND COMPRESSED HIGH RATE SCIENCE

		COMPRESSION FACTOR	COMPRESSED
Engineering Data	64,700	1.0	64,700
(Low Rate Science)			
Atmospheric Pressure		,	
Atmospheric Temperature		į	
Atmospheric Humidity			
Wind Velocity	108,100	1.87	57,600
Subsurface Temperature	Ì		
Subsurface Humidity	13,900	15.85	880
Spectroradiometer	28,000	5.0	5,600
Wolf Trap	48,000	26.2	1,830
a Spectrometer	43,008	2.67	16,100
Gas Chromatograph	256,000	2.0	128,000
Gulliver IV	1,920	9.27	207
Gulliver III	27,360	45.6	600
Optical Rotation	25	1.0	25
Ultraviolet Spectroradiometer	1,440	5.00	288
Sample Acquisition	2,520	1.0	2,520
Surface Accelerometer	800	1.0	800
Totals	595,700		279,150

Total bits from each experiment for 28 hour mission.

Assume Morning Landing Case "B" (i.e. April 6, 1974 Arrive at 40°S Latitude, 30° from Terminator). Assume first-order interpolator.

TRADE SUMMARY - RELAY LINKS

FUNCTIONAL & TECHNICAL	MATRIX	SELECTION		
DESIGN REQUIREMENTS	NO. 1	NO. 2	NO. 3	SELECTION
Back-up transmission of low rate science, high rate science and TV data over relay link.	FSK 10W, 2 dB (min) 500 bps 3 hr	FSK 40W, 2 dB (min) 3 Kbps 3 hr	PSK/PM 40W, 2 dB (min) 5.3 Kbps 3 hr	SELECTION SELECTED APPROACH NO. 2
Trade Consideration Capability in terms of mission requirements	All data excluding part of the TV (5.4 x 10 ⁶ bits)	All data (32 x 10 ⁶ bits)	All data (32 × 10 ⁶ bits)	2 or 3–1
Weight added to SL	Least	Middle 1/2 lb heavier than No. 1	Greatest	1-2-3
Weight added to SC	Least	Least	Greatest	2 or 1–3
Reliability	Most reliable	Most reliable	Least reliable	2 or 1-3
Acquisition Procedure	None required	None required	Sweep receiver	2 or 1–3
Two-Way Doppler Capability	None	None	Possible but adds additional complexity	2–3 or 1
Additional system complexity	No	No	Yes	2 or 1-3

FUNCTIONAL AND TECHNICAL DESIGN REQUIREMENTS

FUNCTIONAL AND TECHNICAL	MATRIX OF DESIGN		
DESIGN REQUIREMENTS	NO. 1	NO. 2	SELECTION
Back-up transmission of low rate and high rate science over direct S-Band link.	MFSK with data compression 50W, 0 dB 10 bps 7 hr	Coded PSK/PM 50W, 6 dB 35 bps (2B _{LO} =5Hz) 4.5 hr	Selected Approach No. 2
Trade Consideration Capability in terms of mission requirements	Low rate science and high rate science minus 28K bits (compressed) (252K bits)	Low rate science and high rate science (570K bits)	2–1
Weight added to SL	Same	Same	1 or 2
Weight added to FSC	None	None	1 or 2
Reliability	Most Reliable	Least Reliable	1 – 2
Acquisition Procedure	Ground sweep	Ground sweep	1 or 2
Two-way Doppler Capability	No	Yes	2 – 1
Additional System Complexity	Yes	No	2 – 1

- 5.4.4.4 <u>Design Approaches and Significant Characteristics</u> The five backup modes considered are summarized below:
 - o <u>S-Band Direct-1</u> An MFSK link with a 50 watt power output TWT and the existing 0 dB antenna will support 10 bps but requires automatic switching of a 50 watt TWT into the existing system, an additional bit stream from the SI celemetry subsystem of 10 bps, and data compression of the high rate science data.
 - o <u>S-Band Direct-2</u> A coded PSK/PM link with a 50 watt power output TWT and a 6 dB transmitting antenna gain will support 35 bps for a DSIF receiver noise bandwidth of 5 Hz ($2B_{LO}$ = 5 Hz), but requires automatic switching of the existing system to a 50 watt TWT and an additional bit stream from the SL telemetry subsystem of 35 bps.
 - o <u>UHF Relay-1</u> An FSK link with 10 watt power output and 2 dB transmitting antenna gain will support 500 bps when the existing Capsule Bus SC mounted radio is used. However, provision must be made to detect and synchronize a second 500 bps bit stream, to turn-on the tape recorder in the SC mounted storage subsystem upon establishment of bit sync., and to obtain the 500 bps bit stream from the SL TM.
 - o <u>UHF Relay-2</u> An FSK link with a 40 watt power output and 2 dB transmitting antenna gain will support 3 kbps, using the Capsule Bus SC mounted radio Provision must again be made for automatic turn-on of the tape recorder and for obtaining a 3 kbps bit stream from the SL TM.
 - o <u>UHF Relay-3</u> A PSK/PM link with 40 watt power output and 2 dB transmitting antenna gain will support 5.3 kbps, but requires a phase lack loop receiver and automatic turn-on of the tape recorder.

The dc power supply and data stream will be automatically decoupled from the system when a failure occurs in the high rate link. If a direct S-band backup approach is selected, the sensing of a failure will automatically switch the dc power and bit stream to the backup mode, thus initiating transmission.

If a relay approach is selected, the transmitting and receiving antenna patterns must overlap before data transmission begins. This will occur whenever a CW transmission from the FSC is detected by the existing relay antenna system on the SL. A 1 watt UHF transmitter (360 MHz) with an integration time of 5 seconds at the receiver will be sufficient for this task. The CW signal will also be used to end transmission by requiring that transmission ceases if the signal is lost.

- 5.4.4.5 <u>Comparison of Design Approach</u> Figures 5.4-35 and -36 present a summary of the comparisons between members of the direct and relay approach categories, respectively. Some of the entries in these figures are explained in the following paragraphs.
 - o Weight Added to SL The approximate increase in weight for each direct S-band backup link is listed below (neglecting added antenna weight).

Direct Backup Link	Weight of TWT (1bs)	Weight of RF Switches (1bs)	Total Added Weight (1bs)
1	23	1.0	24
2	23	0.5	23.5

No additional battery weight was added because the total energy required for each backup system is approximately equal to the energy required for the preferred system. As shown below, the total preferred system energy requirement is 1190 watt-hours (770 + 420).

System	DC Power Required (watts)	Transmission Time (hours)	Total Energy Required (watt-hours
Preferred High Rate Lin	k (20W)110	7.0	770
Preferred Low Rate Link	(10W) 60	7.0	420
Direct Backup 1 (50W)	165	7.0	1150
Direct Backup 2 (50W)	165	4.5	740

Each of the three UHF Relay links requires a UHF transmitter to be added to SL. However, because UHF transmission is more efficient than S-band, the UHF link requires less dc power than is already available for the high data rate link, as is illustrated below:

Backup Relay Link	Required DC Power (watts)	Transmission Time (Hrs)	Required Total Energy (watt-hrs)
1	36	3.0	108
2	115	3.0	345
3	115	3.0	345

Neglecting added antenna weight, the approximate increase in weight for each backup link is listed as follows:

COMPARISON OF DIRECT S-BAND BACK-UP LINKS

SYSTEM PARAMETERS	S-BAND 1 MFSK WITH DATA COMPRESSION	S-BAND 2 50w, 6dB CODED PSK/PM	COMMENTS
Transmission Time	7 hours	4.5 hours	Assumed
Total bits	252 K	<i>5</i> 70 K	
Capability in terms of mission requirements	Low rate science and high rate science minus 28K bits of com- pressed data	Low rate science and high rate science	
Weight added to SL	24 lb	23.5 lb	Neglects weight of addition antenna for B
Weight added to SC	None	None	
Reliability	8666'0	0.9964	Assumes 50 watt TWT is as reliable as 20 watt TWT
Acquisition Procedure	Ground sweep	Ground sweep	
Two-way doppler capability	No	Yes	
Additional system complexity	Yes Due to data compression	o Z	

COMPARISON OF RELAY BACK UP LINKS

System Parameters	UHF RELAY-1 FSK 10W, 2 dB 500 bps	UHF RELAY -2: FSK 40W, 2 dB 3Kbps	UHF RELAY -3, PSK/PM 40W, 2 dB 3Kbps	REMARKS
Transmission Time	3 Hours	3 Hours	3 Hours	Assumed
Total Bits	5.4 × 10 ⁶	32 x 10 ⁶	32 x 10 ⁶	
Capability in Terms of Mission Requirements	High rate science, low rate science, and some TV data	All Data	All Data	
Weight Added to SL	5.9 1Ь	6.5 lb	7.5 lb	Neglects weight of additional antenna
Weight Added to SC	3.0 1Ь	3.0 lb	6.0 lb	
Reliability	0.9949	0.9949	Least	Insufficient Data
Acquisition Procedure	None Req'd B = 7Khz	None Req'd B = 7Khz	Sweep Receiver	
Two-way Doppler Capability	None	None	Possible but Adds Com- plexity	
Addition System Complexity	No	No	Yes, PLL Receiver in SC	

Backup Relay Link	Weight of Transmitter (1bs)	Receiver Weight	Total Weight Added to SLS (1bs)
1	4.4	1.5	5.9
2	5.0	1.5	6.5
3	6.0	1.5	7.5

o Weight Added to Spacecraft - No additional requirements are placed on the spacecraft if a direct to Earth S-band system is utilized. Relay 1 and 2 use the existing SC Capsule Bus radio receiver. Relay 3, however, requires the addition of a phase lock loop receiver to the SC radio subsystem. All systems require that a 1 watt CW transmitter be added to the spacecraft radio sybsystem to achieve automatic turn on. Provision for capability to detect and synchronize a 500 bps or 3 kbps data stream and and for automatic turn-on of the tape recorder upon establishment of bit sync accounts for the assignment of added weight on the FSC shown below.

Relay Backup Link	Total Weight Added to SC Radio SS(lbs)
1	3.0
2	3.0
3	6.0

- o Acquisition Procedure The direct S-band links require no special acquisition procedures other than those used for the baseline MFSK and PSK/PM systems. For the relay links the frequency uncertainty is estimated to be 4.4 kHz including 400 Hz due to doppler. Relay 1 and 2 require no acquisition because the receiver bandwidth (7kHz per channel) is larger than the total frequency uncertainties. However, Relay Mode 3 requires that the phase lock loop receiver be swept over the total frequency uncertainty.
- o <u>Two-Way Doppler Capability</u> Two way doppler tracking would be possible only if the S-band system 2 is used. It is not possible with S-band 1 or with Relay-1 or -2 since they are noncoherent links, making two-way doppler impossible. Relay-3 could be a coherent link if a phase lock loop receiver is also used for the SL. However, to obtain two-way doppler tracking to Earth the UHF VCO would be required to drive the S-band VCO of the FSC. This

method would be very complex and not very accurate.

- o Additional System Complexity Only the direct S-band 1 and the Relay-3 systems require additional system complexity. The former requires data compression (first-order interpolator) of high rate science data; the latter requires the 400 MHz phase-lock loop receiver.
- 5.4.4.6 Recommended Design Approach The results of this analysis show a strong advantage for the use of UHF Relay 2 link as a backup mode to the high data rate link. However, use of a relay backup mode may not be acceptable because of lack of flexibility in specifying the spacecraft orbit. In this event, the direct S-band 2 link would be the recommended backup mode, (assuming a medium gain antenna is acceptable). This mode, can only backup low rate and high rate science.

For the longer missions at higher latitudes, the relay link may be required for continuous communications to Earth. In this case, additional modifications to the communication link hardware will be necessary; for example, orbiter antenna steering and higher transmitter power may be required.

Further study of the relay link for science data backup is desirable to determine the influence the required orbits may have on the entire mission.

5.4.5 Command Subsystem - The command subsystem described in Part C, Section 6 of this volume is designed to provide for the Earth control of the Surface Laboratory (SL). The following subsections are a discussion of some of the more important factors that were considered in establishing this design.

The JPL two channel command detector with PN synchronized PSK/PM was selected because of its flight proven configuration and its superior operating characteristics in the threshold region. The command requirements were estimated and compiled to establish a command word format. The command word is 43 bits long with 11 bits for addressing and 32 bits for data. Analysis of the constraints on the processing of commands by the command subsystem revealed a need for an error detection and correction code. A 63, 57 Bose-Chandhuri code was selected.

Command word synchronization was investigated. We concluded that the most practical method of word synchronization is to transmit the data subcarrier with all zeros as modulation whenever the sync subcarrier is being transmitted to acquire lock. This together with a 4 bit command word preamble of all ones will provide the proper operating performance.

The operating point for the out-of-lock indicator was calculated on the basis

of message format coding and operating constraints. The out-of-lock indicator bias should be set such that the probability of an out-of-lock indication occurring during any bit interval is less than 9×10^7 .

5.4.5.1 Modulation Technique and Detector Configuration — The modulation technique and data detector recommended for use on the VOYAGER SL command link are those used on previous Mariner vehicles, the JPL two channel command detector with PN synchronized PSK/PM modulation. The only other system considered was the single channel system developed for JPL by Philco. This single channel system does not differ appreciably from the two channel system in complexity, reliability, weight and power required. However, the two channel system has been flight proven on the Mariner vehicles. The two channel system operates with carrier power 3 dB above the sync channel power. In turn, sync channel power is 3 dB above the data power. Thus, the carrier power is 57% of the total power received. For the single channel system 75% of the total received power is in the carrier. So, for the same received power the carrier of the single channel system is approximately 1.2 dB higher than that of the two channel system.

The analysis of Reference 5.4-17 describes the major disadvantage of the single channel system. Strong spectral components at the subcarrier frequency due to input noise are generated at the input to the loop phase detector. These components severly degrade the operation of the loop at operating threshold signal-to-noise conditions.

However, our feeling is that the single channel system holds promise of improved efficiency when a delay lock loop is employed. Reference 5.4-18 indicates a theoretical improvement of 3 dB in power requirements. This result was obtained from a detailed analysis of sync jitter losses, bandpass filter losses, crossmultiplier degradation, limiter degradation, etc. In addition, the delay lock loop phase detector error function has a constant, high slope throughout the lock-up region.

5.4.5.2 <u>Command Word Format</u> - The selection of the command word format is based upon estimates of user subsystem requirements with an arbitrary growth factor included. The first elements of the word are the various addresses. A vehicle address of three (3) bits is used to identify the decoder within the Flight Capsule for which the command is destined, since these decoders operate in parallel prior to separation. The next address is to identify the subsystem for which the command is destined. Presently, twelve (12) subsystems in the Capsule Bus and Entry Science Package must be addressed by the Capsule Bus Decoder. Consequently four (4) bits

have been set aside for subsystem address. One bit is used to distinguish between a quantitative command and a direct command. The remainder of the word is sized at 32 bits. That is the number of bits required to update the sequencer and timer memory., and is more than sufficient to satisfy the direct command requirements of the vehicle.

In summary the command word format is:

• Vehicle address	3 bits
• Decoder address	3 bits
• Subsystem address	4 bits
• Quantitative - Direct address	1 bits
• Quantitative - Direct data	32 bits
• Total	43 bits

5.4.5.3 Command Word Code - The command link is designed to provide a threshold bit error probability of less than 10^{-5} . Two significant constraints on the processing of commands by the command subsystem resulted in implementation of the command word code. These constraints are, (1) that the probability of accepting a command with one or more undetected errors shall be less than 10^{-5} , and (2) that the probability of no response to a command due to one or more detected errors and/or out-of-lock indication shall be less than 10^{-4} .

Considering first the effects of bit errors, it is apparent that some form of bit error detection is required in processing commands.

Let,

 $^{\circ}$ P $_{1}$ = the probability of accepting a command with one or more undetected errors

 $^{\circ}$ P_{2} = the probability of no response to a command due to one or more detected errors.

If no bit detection is employed, a command word "n" bits in length will have:

$$P_1 = 1 - (1-P_e)^n$$

where

$$P_e = bit error probability = 10^{-5}$$
.

When

$$P_e << 1$$
, $(1-P_e)^n = 1 - n P_e$.

Therefore

$$P_1 = n P_e = n (10^{-5}).$$

So, for a message of any length, some form of bit error detection is required. Using a single bit parity code a command word "n" bits in length (assuming the

parity bit is not one of the "n" bits) will have:

$$P_{1} = (1-P_{e}) \sum_{k=1}^{n/2} {n \choose 2k} P_{e}^{2k} (1-P_{e})^{n-2k} + P_{e} \sum_{k=1}^{n/2} (2k-1)^{\frac{n}{2}} P_{e}^{2k-1} (1-P_{e})^{n-(2k-1)}$$

Then

$$P_1 \begin{pmatrix} n \\ 2 \end{pmatrix} P_e^2 + \begin{pmatrix} n \\ 1 \end{pmatrix} P_e^2 = \frac{n}{2} (10^{-10})$$

Then $P_1 \begin{pmatrix} n \\ 2 \end{pmatrix} P_e^2 + \begin{pmatrix} n \\ 1 \end{pmatrix} P_e^2 = \frac{n}{2} (10^{-10})$ So for word lengths up to 450 bits the criteria that $P_1 < 10^{-5}$ is met, However, using a single bit parity code:

$$P_2 = 1 - \left[P_1 + (1 - P_e)^n\right] = 1 - \frac{n^2}{2} P_e^2 - 1 + n P_e,$$

 $P_2 = n P_e (1 - \frac{nP_e}{2}) = nP_e.$

The criteria for P_2 is $P_2 < (10^{-4})$,

therefore,

Since this is unsatisfactory, a form of error correction must be employed.

One method of error correction requires three transmissions of the command The first two transmissions are stored as received. As the third transmission is received, it is "majority voted" on a bit-by-bit basis with the first two stored The probability of a bit error being introduced in the voting process;

P'_e is approximately
$$\begin{pmatrix} 3 \\ 2 \end{pmatrix}$$
 P_e² (1-P_e)

P'_e = 3P_e² = 3 x 10⁻¹⁰

Then using this method,

$$P_1 = 1 - \left[1-3 (10^{-10})\right]^n = 3n \ 10^{-10}$$
 and $P_2 = 0$.

The disadvantage of this method is the transmission time required for each command word.

Another method of error correction is the use of error correcting codes. a single bit error detection and correction code is used,

$$P_1 \approx {n \choose 2} P_e^2 (1-P_e)^{n-2}$$

Then

$$P_1 = \frac{n^2}{2}$$
 (10⁻¹⁰), and $P_2 = 0$

Using this method and employing a 63.57 Bose-Chandhuri code, a 57 bit command word

can be corrected by transmitting an additional 6 bits for error detection and correction. This method was chosen because it best meets our understanding of the reason for the constraint. Namely, reduce as much as practical the time required to get a correct command word into the command subsystem and acted upon.

5.4.5.4 Command Word Synchronization - A command word "preamble" is required at the beginning of each command word. Its function is to synchronize the decoder with the command word format so that the decoding process will be accurate and complete.

If the Earth is transmitting a signal to lock-up the command detector (PN + 2 fs), and no data subcarrier is being transmitted, the detector will begin to transmit random "ones" and "zeros" to the decoder after lock-up is achieved since it is making decisions on noise. There is a finite probability, P_3 , that a succession of random bits will generate the word sync pattern.

$$P_3 = 1 - \left[(1 - (\frac{1}{2})^m) \right]^t \approx t(\frac{1}{2})^m$$

where

m =the number of bits in the preamble

and t = the number of bits in the random bit stream.

Also,
$$P_2$$
 for the sync word is: $1-(1-P_e)^m = mP_e = m(10^{-5})$.
If, $P_2 < 10^{-4}$, $m(10^{-5}) < 10^{-4}$ and $m < 10$, then $P_3 > t$ $(\frac{1}{2})^{10}$

If P₃ is arbitrarily set at
$$10^{-5}$$
, $10^{-5} > t \left(\frac{1}{1.024 \times 10^3}\right)$

then

$$t < 1.024 \times 10^{-2}$$
.

That is to say, no random bits can be allowed to enter the decoder. Once again error detection and correction technique can be used to allow random bits to enter the decoder for an extended period of time. However, this requires a long preamble extending the time necessary to transmit a command word. It seems that a more reasonable solution to the problem is to transmit the data subcarrier with all zeros whenever the sync subcarrier is being transmitted to acquire lock. The word sync pattern can then be in consecutive ones.

Then

$$P_3 = 1 - \left[1 - (P_e)^m\right]^t \approx t (10^{-5})^m$$
 and $P_2 = 1 - (1 - P_e)^m = m(10^{-5})$.

We chose m = 4. So, $P_2 = 4 \times 10^{-5}$ which meets the criteria of 10^{-4} . And, $P_3 = t (10^{-20})$ so lock-on can be held indefinitely without concern that word sync will be generated by a stream of random bits.

5.4.5.5 Out of Lock Indicator - The operating constraint that the probability of no response to a command due to one or more detected errors and/or an out-of-lock indication shall be less than 10^{-4} necessitates the following analysis of the out-of-lock indicator performance. First, let us define P_4 as the probability that an out-of-lock indication will occur during any bit interval.

Then, the probability of no response to a command due to an out-of-lock indication, P_5 is;

$$1-(1-P_4)^{67} \approx 67 P_4.$$

 P_2 for the entire message is $1-(1-P_e)^4 \approx 4(10^{-5})$,

since P_2 for the 63 bits after the preamble is 0. P_5 and P_2 are correlated because the noise has a common effect on both probabilities. However, for a worst case analysis they can be considered uncorrelated. Then, the probability of no response to a command,

$$P_6 = P_5 + P_2 - P_5 P_2$$
.
 $P_6 = 67P_4 + 4(10^{-5}) - 67P_4 \cdot (10^{-5}) = 67P_4 \left[1 - 4(10^{-5})\right] + 4(10^{-5})$
 $P_6 \approx 67P_4 = 4(10^{-5})$

By constraint, $P_6 < 10^{-4}$.

Therefore,

$$67P_4 + 4(10^{-5}) < 10^{-4},$$
 $P_4 < (0.6)(10^{-4})$, $P_4 < 9(10^{-7})$

So the bias in the lock detector must be set such that $P_{\Lambda} < 9 \ (10^{-7})$ at threshold.

5.4.6 Antenna Subsystem - The SL Antenna Subsystem must become operational as soon as possible after landing, and support transmission of high rate and low rate data to Earth, while accepting command transmission from the DSN.

The analyses which follow lead to the selection of a steered high gain antenna for high rate data transmission, since fixed antennas cannot satisfy the minimum daily data transmission requirement. Initial hour angle axis alignment of the high gain antenna will be accomplished by gyrocompassing, which offers rapid erection time and independence from external aids. Clock tracking is selected for the primary tracking mode after alignment, while autotracking is chosen as a pointing refinement to realize maximum antenna gain. Pseudo-conical scan is the preferred approach for autotracking, based on the incorporation of the better features of both conical scan and monopulse in a single channel receiver implementation. The proven development of the selected parabolic dish with a circularly polarized feed argues against the smaller planar array, in the choice of high gain antenna.

The low rate data link and command link will be supported by separate antennas, which provide RF isolation and avoid a common single point failure. Deployment of the antennas on a rotating mast will afford sufficient unobstructed field of view. Pattern coverage and polarization requirements are satisified by the preferred Archimedes spiral antennas, which possess bandwidth properties that will avoid deturning.

- 5.4.5.1 <u>Fixed Vs. Steered Antennas</u> An analysis of the SL high-rate communications requirements was conducted to choose a satisfactory S-band antenna design from the three candidate approaches. The requirements of interest are:
 - o The landing site may be any where from $+10^{\circ}$ to -40° latitude, and at any longitude.
 - o The landing may occur anytime between 16 January 1974 and 6 April 1974.
 - o The (30) landing error shall be considered to be 500 km.
 - o Communications may take place only when the elevation angle is greater than 34° from true horizontal.
 - o The minimum data rate is 5×10^6 bits per day for any choice of landing sites or dates.

The three candidate approaches are fixed (no erection), fixed (erected to local vertical), and mechanically steered.

Design Selection - A set of curves which specify the position of the Earth in the Martian sky for any choice of longitude and latitude may be derived once a landing date is chosen. (See Section 2.3.) A plot of Elevation Angle vs. Time from Subearth longitude may be extracted from that set of curves for a given landing latitude. Such a plot indicates the beamwidths required to transmit for a given number of hours per day if the antenna is aligned to local vertical. However, the plot does not account for uncertainties in landing accuracy. This antenna beamwidth-transmission time information may be corrected by modifying the original set of curves to tolerate a worst case landing error, a landing error of 500 km directly east or west, as drawn on Figure 5.4-37 for both extremes in landing date and -40° latitude.

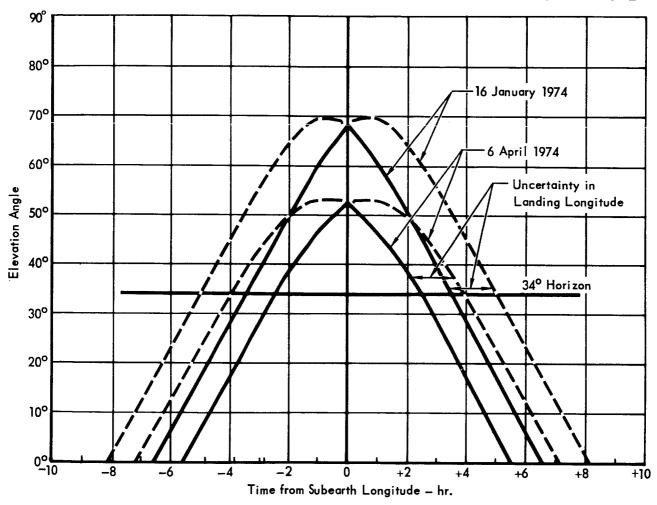
From these curves the allowable communication time for each beamwidth can be found for the fixed and steered antennas. (The allowable communication time is the tiem between the two innner, solid curves on Figure 5.4-37, since they are composed of leading and trailing edges of curves shifted to account for possible longitude errors.) Deriving data rates from this information requires the use of equations given in Reference 5.4-19. Daily data rate/unit power is plotted as a function of beamwidth for several landing latitudes in Figure 5.4-38, which shows that the steerable antenna has much greater transmission capability than the erectable antenna concept at any landing latitude.

The curves on Figure 54.-39 of daily data rate as a function of power for several landing latitudes again indicate that the steered antenna is the preferred approach from the standpoint of transmission capability.

There are considerations other than transmission capability in the selection of a preferred high-rate antenna, however; the additional criteria considered in the design selection matrix, Figure 5.4-40 are Tolerance of Landing Data and Latitude, Tolerance of Surface Terrain, Simplicity and Design Reliability.

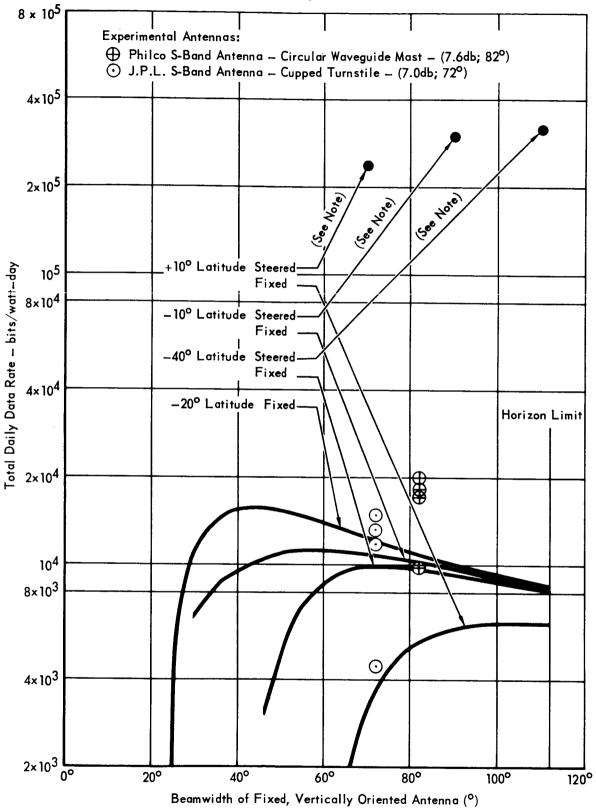
Clearly, the steered antenna approach has the best utility value ("10") in each criteria in the category of technical feasibility (because it is unaffected by surface terrain, variation of landing site and landing latitude and because it can transmit the minimum and design goal data rates with reasonable power expenditures). Each fixed system is greathy affected by changes in landing site or date, and will have a value of "2", but only the fixed - no erection concept will not adapt to terrain. It has a "0" for that criteria while the erectable antenna has a "10".

ELEVATION ANGLE vs TIME FROM SUBEARTH LONGITUDE - FOR -40° LATITUDE



COMPARISON OF COMMUNICATION CAPABILITIES

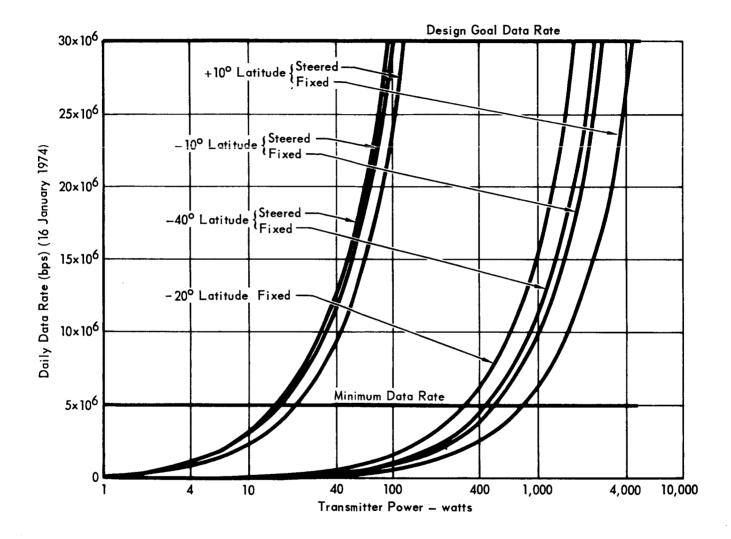
16 January 1974



Note: All steered antennas assumed to have 16° Beamwidth

Figure 5.4-38

DATA RATE vs TRANSMITTER POWER (AT OPTIMUM BEAMWIDTHS FOR FIXED ANTENNAS)



DESIGN MATRIX FOR FIXED vs. STEERED STUDY

	ERE	ED - NO CTION	2 FIXED - ERECTABLE		3 MECHANICALLY STEERED	
SELECTION CRITERIA	UTILITY	× WEIGHTING	UTILITY	× WEIGHTING	UTILITY	× WEIGHTING
Tolerance of Landing Date and Latitude	2.0	× .15 = 0.3	2. 0	× .15 = 0. 3	10.0	× . 15 = 1.5
Tolerance of Surface Terrain	0.0	x . 15 = 0. 0	10.0	x . 15 = 11.5	10.0	× .15 ≈ 1. 5
Transmission Capability	0.0	x .30 = 0. 0	3.0	× .30 = 0.9	10.0	× .30 = 3.0
Simplicity	0.0	x .20 = 0.0	6.0	x . 20 = 1.2	5. 0	× .20 = 1.0
Design Reliability	0.0	× .20 = 0.0	8.0	× .20 = 1.6	7.0	x .20 = 1.4
Total Weighted Value		0.3		5.5		8.4

Both fixed systems require excessive power to transmit even the minimum data rate; but the erectable antenna could serve as an alternate, low-gain antenna while the fixed - no erection approach could not satisfy even such limited transmission goals, to the former will get a value "3" while the latter gets a "0".

The entries for design reliability and simplicity include the impact of antenna selection on the system as a whole. Therefore the increased transmitter powers associated with fixed antennas shown in Figure 5.4-39 more than offset the increases in antenna simplicity and reliability. The resulting entires are shown in Figure 5.4-40.

The total weighted value of the steered antenna indicates that this approach is the best design for the high-gain S-band antenna. Further study of the design matrix and of Figure 5.4-38 indicates that the fixed, vertically, oriented antenna is a competitive approach to the steered antenna for low gain antennas, when the transmission requirements are not so high as 5×10^6 bits/day. Should the technical feasibility criteria cease to be of importance because both design approaches can transmit equally well, the fixed, vertically-erected antenna is the superior approach, especially when the landing point latitude chosen is near the subearth point (-20° for 16 January 1974).

Summary - The study of possible antenna approaches to satisfy the communication requirements of VOYAGER shows that the high-gain, steered antenna is the only approach which completely satisfies the requirements. Even at a subearth latitude landing, landing uncertainties cause the fixed, vertically-oriented antenna (a good medium-gain approach) to require excessive power to transmit the minimum data rate.

5.4.6.2 Antenna Pointing Techniques - Several pointing techniques are available which are potentially capable of orienting the high gain antenna and maintaining the beam in a specified position relative to Earth. This section briefly examines these various techniques and discusses reasons for including a Radio Frequency (RF) pointing (autotracking) mode of operation within the SL. The rationale for the selection of pseudo-conical scan as the preferred autotracking method is also included.

A high gain parabolic antenna directs its radiated energy into a solid cone centered about the antenna axis. The antenna must be pointed such that the target (Earth) falls within this cone shortly after landing. This beam/target relationship must be maintained throughout the high rate data transmission periods. For

this reason, the following requirements are imposed upon the pointing techniques used:

- o The antenna must be erected and pointed toward Earth nominally within 30 minutes after landing.
- o Initial alignment of the antenna must not depend on any signal or information external to the SI and must be compeltely automatic.
- o The initial alignment must point the antenna with sufficient accuracy to allow data to be transmitted at 600 bps, a self imposed requirement.
- o Means will be provided for refining the antenna pointing so that the maximum data rate capability is 1200 bps.
- o To fulfill the requirements it is imperative that the pointing technique used make optimum use of available transmitting time.

The fourth requirement noted above, in conjunction with packaging limitations, imposes restrictions on the antenna size. A data rate of 1500 bps for the particular bandwidth and transmitter power involved requires a gain of 22.8 dB (i.e., ERP of 35.8 dBW). Additional gain must be provided to compensate for feed losses (1.3 dB) and for the anticipated loss of gain through pointing error. Weight and stowage restrictions in effect limit the antenna size to 36 inches, which at 55% efficiency provides a gain of 24.3 db at 2295 GHz. The high data rate capability, therefore, requires that the antenna pointing loss be no more than 0.2 dB after position refinement.

The lower data rate goal of 600 bps can be fulfilled with an effective gain of 18 dB or more. Since a 36 inch antenna must be used to satisfy the high data rate requirement, a loss due to pointing error of 5 dB can be tolerated. For the high gain antenna whose half-power beamwidth is 5.1 degrees (one-sided) the allowable pointing errors corresponding to the 0.2 dB and 5.0 dB points are 1.5 and 6.6 degrees, respectively.

Selection of Primary Pointing Technique - There is no single device which, when used as a reference, will itself fulfill all the listed requirements. However, there are several methods that are useful for performing a particular function and which, when used with other techniques, satisfy the overall requirement. These positioning methods are listed below:

- o Sun Sensing
- o Gyro Compassing
- o Clock Tracking

- o RF Tracking
- o Real Time Commanding

Described below are the areas in which specific pointing methods are particularly useful; also included are reasons for the selection or rejection of certain configurations as primary modes of operation. It should be emphasized that rejection of a technique as a primary mode does not eliminate its use as a backup method.

Sun Sensing - Sun sensors can be used as references for positioning the two lower axes (AZ and EL) which align the HA axis to the Mars spin axis. Another Sun sensor placed above the HA axis could be used to rotate the antenna about the HA axis until the beam is pointed toward Earth. If this HA sensor is adjusted so that the beam is directed two hours ahead of the Sun, normal Earth tracking can be maintained. The antenna axes are described in Section C 10.

This method of directing the antenna typically has three difficulties associated with it. First, the initial erection/alignment procedure requires that the path of the Sun be known precisely, which entails making two measurements, each a quarter of a day apart. If the SL landed in the afternoon of the first day, the alignment might not be completed until well into the second day. Secondly, the Earth trails the Sun by two hours. If the SLS lands in a crater where the ridge is only 56 degrees from vertical (34° from horizontal), at least two hours of operation are lost each day. Finally, Mars may be plagued with frequent dust storms that are severe enough to maks the Sun and render Sun sensors useless.

For the above three reasons, Sun sensors are not used in the erection procedure. Gyro Compassing - Gyros are of no value in determining longitude position, and therefore, cannot be used for tracking. Nevertheless, gyros are excellent reference devices for controlling the erection axes (AZ and EL) as they operate independently of external sources and rely only upon detecting the rotation of Mars. Gyros are limited even in this application because of a possible 39 degree tilt of the SL. This is discussed in Part B, Section 5.3.

In contrast to the six hour erection time required for Sun sensors, gyros can align the hour angle axis within 20 minutes after the gyros have stabilized. Allowing a stabilization time of eight minutes, the total erection can be accomplished in less than 30 minutes (the gyro compassing procedure is described in detail in Part B, Section 5.3.

Because of its rapid erection time and its independent nature, a gyro compassing system has been included for initial HA alignment in the preferred system design.

Clock Tracking - Clock tracking is valuable as a tracking technique only when the axis upon which it operates has been previously aligned to the planet's spin axis. Then the Earth can be tracked with a single axis (short term) and each clock pulse can move the antenna a specific interval (which simplifies servo design). The clock tracking method, once initiated, is independent of sources external to the SL, but if it is to be effective, the position of the Earth relative to the SL vertical axis for a given time must be established. Therefore, this method can only be as accurate as the initial alignment accuracy, or as accurate as any refinement of position which has been accomplished.

Clock tracking is valuable as a tracking mode because only a simple single axis movement is necessary.

RF Tracking - RF Tracking (that is, using a beacon signal radiated from the target as a reference) does not satisfy the requirement that the SLS operate independently of the DSIF, but because of its potential accuracy, is invaluable as a technique for refining the position of the high gain antenna relative to Earth. Since clock tracking is only as accurate as the initial alignment, which in turn depends on a combination of gyro compassing and programmed conditioning, autotracking is the only fast, reliable method of obtaining maximum gain from the 36" antenna. An autotracking accuracy analysis performed in Part B Section 5.3 shows that beam/target alignment can be accomplished to within 1.0 degree. The only other methods which approach this accuracy are the Sun sensing method which may not be too reliable, and real-time commands which are excessively time consuming.

Thus, RF tracking is included in the system for hour axis position refinement, and is used in conjunction with clock tracking to eliminate the dependence upon proper DSIF operation.

Real Time Command Pointing - Through real time commands from the DSIF, the antenna can be directed toward any point and subsequent position updating can accurately align the antenna to Earth. However, not only does this method require proper operation of the DSIF, but it is also dependent upon the proper functioning of the SI command system and low rate telemetry system. If this method was the primary mode, failure anywhere in the link would preclude further operation.

If direct commands were the sole source of erecting and aligning the antenna, considerable time and power would be required for searching the sky and finding Earth. Even if the antenna was aligned in the general vicinity of Earth by other methods, commanding the antenna to various positions and monitoring the received signal strength would be a time consuming process (considering the 30 minute round trip transit time). The transit time and the dependence on other subsystems are sufficient reasons for not using real time commands as a primary pointing mode.

From the above discussion the reasons for selecting the particular high gain antenna control system are evident. The primary mode of operation involves the use of gyro compassing for HA axis alignment, stored information for initial HA positioning, clock tracking as the primary pointing method, and autotracking for position refinement. All of these techniques are defined with more detail in Section B 5.3. The selection criteria for the type of autotracking employed is summarized below.

<u>Selection of RF Autotracking Method</u> - There are four commonly used methods of tracking a RF signal, each with its own merits and limitations. These are:

- o Con-Scan
- o Sequential Lobing
- o Monopulse
- o Pseudo Con-Scan

This section considers these autotracking methods and examines the relative merits of each. It is concluded that, for the SL, the pseudo con-scan technique is the most appropriate approach.

Con-Scan - The con-scan technique involves offsetting the feed from the mechanical axis and physically spinning it about this axis. The result is a beam which scans about the normal RF axis. When this axis is aligned with the source a normal RF signal is received, but when it is misaligned, the received signal is amplitude modulated by a frequency equal to the scan rate. By properly detecting this modulation, the pointing error can be resolved into two orthogonal components and used to drive a servo system.

The major advantage of the con scan system is that only a single channel is required in the tracking receiver to detect this modulation. The major disadvantages are the continuous mechanical rotation of the feed and the resulting loss in transit signal due to the mechanical offset. Additionally, the mechanical rotation increases the weight of the feed and requires continuous power consumption.

Sequential Lobing - This technique uses a four element feed in which each

element is sequentially sampled. This technique is only applicable to parabolas since there is a serious loss in gain when arrays are used due to reduced aperture efficiency. If the signal from each element is equal, then the pointing error is zero, while unequal signals can be resolved into pointing errors.

With switching diodes, sequential lobing can be accomplished without moving parts. However, failure of one element results in serious modulation of the transmitted signal. In addition, the tracking receiver will lose lock and must reacquire lock each time the missing element is scanned.

Monopulse - Monopulse tracking is a form of instantaneous tracking in which each lobe is sampled at RF frequencies. This technique uses a comparator network which adds the signals from the four antenna elements while generating the differences in signals between the axis of symmetry. As a result, two error channel receivers are required in addition to the sum channel receiver in order to detect the signals. The error channel receivers are not complete receivers because their local oscillator is replaced by the sum channel voltage controlled oscillator. The major disadvantage of this system is that it requires three separate channels, all of which must maintain a reasonably matched phase response over the full mission. With present state-of-the-art equipment, this is impossible without including a complicated servo-controlled phase adjustment. Another serious disadvantage is the requirement to pass three RF transmission lines across the pedestal axes. This problem, when considering the environment, appears to significantly complicate the design.

Pseudo Con-Scan - This technique incorporates the advantages of both the conscan and monopulse systems: a stationary feed and a single channel receiver. This technique uses a standard monopulse feed, namely, four elements and a comparator network. The two error signals are amplitude modulated by audio frequency signals which are shifted 90° in phase relative to each other. These are combined with the sum channel signal through a directional filter. This technique generates a signal identical to the con-scan system and hence the simple single receiver can be used. The use of a directional filter allows only the received signals to be coupled, preventing the transmitted signal from being coupled into the modulator and partially wasted. The monopulse comparator and modulator are discussed in detail in Part C Section 5.1 and the Tracking Receiver in Section C 4.3.

The advantages of pseudo con-scan over standard monopulse are:

- o A significant reduction in the total number of modules by the elimination of the matched difference channels.
- o Reduced size and weight. (188 in 3 vs. 439 in 3 and 5.3 lbs vs. 13.5 lbs)
- o Reduced power consumption (8 watts vs. 10.1 watts)
- o Higher predicted reliability.
- o Less sensitive to amplitude and phase unbalances in feed network.
- o Reduced complexity of the antenna feed connection between the receiver and the antenna pedestal.

Since the mechanical con-scan and sequential lobing techniques have disadvantages as noted above and the pseudo con-scan has advantages over standard monopulse, the pseudo con-scan method was selected as the preferred design approach.

5.4.6.3 <u>High Gain Antenna Study</u> - The purpose of this section is to determine the type of high-gain S-band antenna best suited for the SLS application. Two candidates were considered for this application: a prime-focus-fed parabola and a planar array. The characteristics of these antennas and justification for the selection of the parabola as the preferred design concept are summarized below.

The criteria upon which the antenna was chosen are as follows: The antenna must -

- o Have a minimum gain of 24.3 dB
- o Be suitable for monopulse tracking
- o Require little or no development work
- o Be lightweight and compact

Parabolic Antenna - The parabolic antenna has a long history of reliable performance in both ground and space applications, including the Mariner and Lunar Orbiter programs. Construction techniques, especially those involving lightweight materials, are reasonably simple and no problems are expected. Typical construction involves the use of a lightweight plastic honeycomb that is sandwiched between two layers of a glass-cloth plastic material. The reflecting surface is coated with a thin metallic layer. A parabolic antenna so constructed is very lightweight; main reflector, feed, support legs, and comparator network weigh a total of 6.5 lbs.

The ultimate gain requirement and feed losses require that the antenna have an effective gain of 24.3 dB, which can be achieved with a 36 inch parabola of 55 percent efficiency. Whereas the diameter is determined by gain requirements, depth is a function of the feed beamwidth. For a monopulse feed the primary sum pattern is narrower than for a single element feed and, therefore, the required

focal length is longer. For this application, the focal length-to-diameter ratio (f/d) will be normally 0.5, which means that the distance from the reflecting surface of the main dish to the feed aperture must be at least 18 inches along the RF axis. When the reflector thickness, feed depth, and comparator/modulator package size are included, a total antenna depth approaching 26 inches is necessary.

<u>Planar Array</u> - The configuration considered for the SLS application is a resonant slot array. This device has linear radiating elements placed every half wavelength along each waveguide section. These slots are on alternating sides of the waveguide to eliminate grating lobes. Circular polarization is achieved by attaching a polarizing grid across the face of the array.

To achieve a gain of 24.3 db, the planar array would have to be nominally 27 inches square (assuming 70 percent efficiency). This is equivalent to a surface area of 729 square inches which, when compared to the parabolic dish projection of 1015 square inches, reduces the wind loading and required stowage area by 28 percent. The total depth of the array is about 6 inches, one quarter of the parabolic antenna depth. In addition, the array is flat and lends itself to easy stowage on top of the SL.

It is also desirable that the weight of the planar array be minimized. To accomplish this the planar array must be made of either a thin-walled aluminum structure or a metal-plated plastic material. In either case, fabricating such an enclosed structure to the tolerances required for efficient operation is expected to present some difficulties. The task can, however, be accomplished as was demonstrated by the Surveyor program. The weight of the finished structure including the comparator and modulator is expected to be approximately the same as the parabolic dish (6.5 lbs).

Planar arrays have been used in radar systems for the past 20 years, and during the past eight years have found their place in space applications (the most recent being the Surveyor program). However, none of this experience is really applicable to VOYAGER requirements. In particular, the combination of a waveguide (slot) planar array, circular polarization and monopulse tracking has not previously been proven for space applications. The waveguide planar array developed for the Surveyor program was circularly polarized but did not include monopulse tracking capabilities. Even so, this device is still in the developmental stage and would require additional experimentation before it would be suitable for the VOYAGER program. The problems associated with dividing the array into four sections,

feeding each into the comparator, and maintaining proper phase relationships should be explored prior to its incorporation into the SL system.

<u>Conclusion</u> - From a size and packaging viewpoint the planar array is the most suitable for the VOYAGER program. However, because of the development required to produce an operational, monopulse waveguide array with circular polarization, the parabolic antenna was selected as the preferred design.

5.4.6.4 <u>Tracking Receiver Studies</u> - A tracking receiver is required in the SL, operating on the command transmitter signal from the DSN. This receiver is a required part of the pseudo-conical scan antenna tracking system described in Part B Section 5.4.6.2. Several important factors were analyzed and are summarized in the following paragraphs. These include: frequency uncertainties prior to acquisition and bandwidth required, acquisition time as a function of bandwidth and received signal-to-noise ratio, and antenna scan rate limitations. It is found that very good performance results from reasonable parameter selections, e.g. 3 1/2 minute search time for a 26° x 52° area with worst case values for the base-line antenna and tracking receiver.

Tracking Receiver Frequency Acquisition - The initial uncertainties in the frequency and frequency rate of the DSN signal arriving at the receiver and the in tracking receiver local oscillator were first examined. The received frequency uncertainty is larger than the capture range of the phase-locked loop, so a frequency-swept search mode is used for initial acquisition. Selection of input sweep rate is dependent on the initial uncertainty, the required search or acquisition times, and the anticipated signal strength. Either the DSN ground (command) transmitter is swept or the VCO (voltage controlled oscillator) in the tracking receiver is swept in a closed-loop acquisition mode.

The Doppler shift at a transmitter frequency of 2.1 GHz was calculated to be \pm 107 kHz maximum due to the relative motion of the two planets centers, and \pm 4.2 kHz maximum due to each planets rotation about its polar axis. Compensation for these uncertainties by programming the DSN transmitter frequency according to the ephemeris data is a regular practice. Since these data are so well known, the programmed tuning of the DSN transmitter can be expected to reduce the uncertainty to less than one percent of the total, i.e., less than 1 kHz, and probably less than 0.1%. The second factor, the component of Doppler shift due to planet rotation, is also compensated by programmed tuning of the DSN transmitter. However, a residual uncertainty, of \pm 2 kHz due primarily to Lander position uncertainty is assumed.

Since the tracking receiver is to be phase-locked and operating on the command signal, it is assumed to be equivalent in design and performance to the phase-locked command receiver portion of the Mariner 1969 S-band coherent transponder. It has a maximum uncertainty specified as \pm one part in 10^5 . This corresponds to approximately \pm 21 kHz at the command link frequency. The total uncertainty is about \pm 23 kHz. A conservative value of \pm 30 kHz was used for analysis.

The tracking receiver must have sufficient bandwidth (IF and PLL) and gain to track the input rate of change of frequency and its total range, respectively. However, it has been verified that these requirements are small with respect to the acquisition considerations. The total maximum computed Doppler rate of 0.13 Hz/Sec. is insignificant. It can be readily tracked with a PLL bandwidth of two Hz.

If it is assumed that the tracking receiver VCO has a short term instability of \pm one part in 10^7 (as in the Mariner transponder) represented by a frequency ramp covering this range in a period of one-second, the corresponding ramp would be about 200 Hz/Sec. Even this rate is considerably lower than the frequency sweep rates that will be used during initial acquisition.

An optimum phase-locked loop noise bandwidth exists for frequency acquisition which is based on minimization of total peak phase error in the loop due to both thermal noise and frequency search dynamics. This optimization is equivalent to minimizing the required input carrier level for a given probability of carrier lock-on by the loop. For closed loop frequency search this optimum bandwidth is given by,

$$2B_{n} = 5.55 \sqrt{f}$$

where: $2B_n$ = two-sided equivalent noise bandwidth of the tracking receiver (sum channel) phase-locked loop, at threshold, and

f = total rate of change of input frequency due to both input signal dynamics and frequency sweep during search.

It has been shown that the input signal dynamics due to Doppler rates are negligibly small, so that the rate-of-change of input frequency is that due to frequency sweep during acquisition. This is true whether the ground transmitter is swept in frequency or the SL tracking receiver VCO is swept. For ramp frequency search:

$$f = \Delta f/t_f$$

where: $\Delta_{\hat{f}}$ = the peak-to-peak frequency sweep width (excess of the expected uncertainty) and

 $t_{\rm f}$ = the time required for a single frequency sweep.

It will be assumed here that a probability of loop capture on a single frequency sweep of 99.9% is sufficient for a design threshold. This corresponds to a received carrier to noise ratio of about ρ = 10.7 dB as determined experimentally (see Figure 5.4-41). Based on the above and the link calculations of Section 5.4.8 (accounting for differences in bandwidth and receiving antenna gain) the data for Figure 5.4-41 were obtained.

It is seen that for the baseline SL antenna gain (24.3 dB) the frequency acquisition times may be made small, with sweep times on the order of a few seconds or less.

Antenna Scan Rate Limitation - Since the total frequency uncertainty must be searched each time the antenna beam scans through its own capture beamwidth, the maximum antenna scan rate (A) is given by:

$$\hat{A} = \frac{0.85 \, \theta_{hp}}{t_f} \quad \frac{\text{deg}}{\text{sec}} \tag{3}$$

where the numerator is the capture beamwidth, defined as 85% of the half-power beamwidth, θ_{hp} , and t_f is the scan time. The total time required for the antenna to scan through a given angular uncertainty $\Delta\theta$ is then

$$T_{a} = \Delta\Theta \frac{t_{f}}{0.85 \Theta_{hp}} \sec$$
 (4)

This assumes a constant antenna scan rate and a spatial uncertainty, $\Delta\theta$, defined as a rectangular "strip" $\Delta\theta$ long and 0.85 θ_{hp} high.

In other words, $\Delta\theta$ is the angular uncertainty for a single axis search pattern, but must be adjusted when considering other scan patterns. For example, searching a rectangular area 52 degrees "long" and 25 degrees high with a 24 dB antenna would require three sweeps along the 52 degree sector, stepped in height by about 8.8 degrees (the capture beamwidth) with each sweep. Thus the "linear" angular sweep length $\Delta\theta$ would be 3 x 52 = 156 degrees.

Assuming the minimum frequency search time is selected, and thus the maximum permissible "optimum" loop bandwidth, the frequency search time t_f may be expressed as a function of the frequency uncertainty using the data of Figure 5.4-41.

LANDER TRACKING RECEIVER FREQUENCY SEARCH TIME

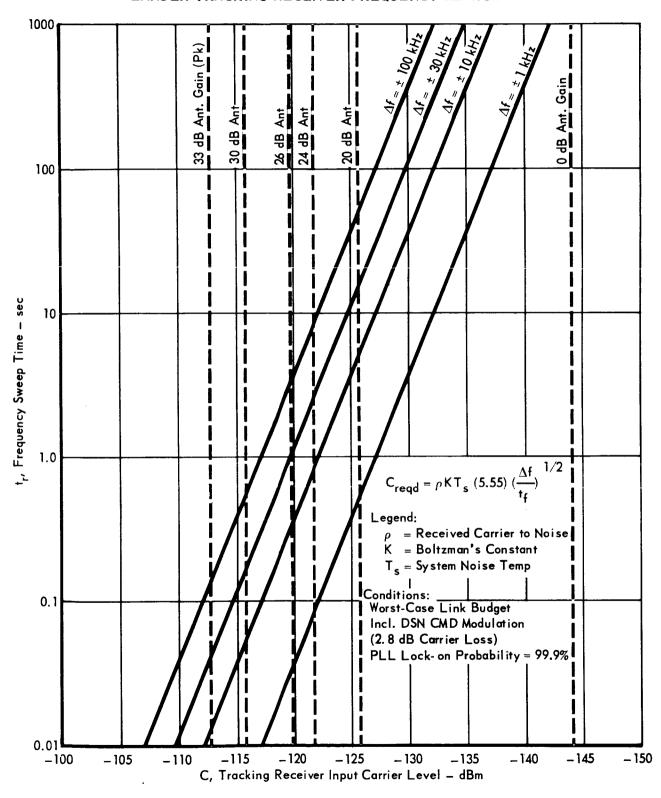


Figure 5.4-41 5.4-90

Further, since a fixed relationship exists between antenna gain and half-power beamwidth, i.e., $G = \frac{26,600}{\theta^2}$ (5)

for an antenna efficiency of 63%, the total acquisition time may be related directly to frequency uncertainty, Δf , angular uncertainty, $\Delta \Theta$, and antenna gain G. These relationships are shown in Figure 5.4-42.

It is found that acquisition time decreases with increasing antenna gain by the three-halves power for singel axis search. For rectangular raster scans, the parameters, $\Delta \Theta$, increases with decreasing beamwidth so that total search time decreases in direct proportion to increasing antenna gain.

It is seen that for the assumed frequency uncertainty of \pm 30 kHz, an antenna gain of 20 dB, and an angular search range $\Delta\Theta$ of 3 x 52 or 156 degrees, the total search time required is 3 x 68 or 204 seconds, about 3 1/2 minutes. This is considered to represent the overall worst-case situation as it is for the lowest antenna gain being considered, with the maximum frequency uncertainty, and corresponds to the most adverse link budget. The phase-locked receiver bandwidth, 28 Lo, that would be required for this worst condition can be computed from equation (1), noting that the sweep time for G = 20 dB and Δ f = \pm 30 kHz is about 15 seconds, which results in 28 Lo = 350 Hz.

The curves in Figure 5.4-42 with the peak antenna gain fixed at 26 dB, show that a marked reduction in minimum permissible search time results relative to the 20 dB antenna. For $\Delta f = \pm 30$ kHz, $\Delta \theta = 156$ degrees, the total search time is $T_a = 24$ seconds. In this case, however, the optimum bandwidth is 1350 Hz. As antenna gain goes up, it is clear that the minimum permissible search time may not be warranted: simple bandwidth conservation should limit the maximum tracking receiver noise bandwidth to one to two kHz, since total search time on the order of ten seconds is assumed to be sufficiently small.

The conclusion is that the tracking receiver is permitted to employ threshold noise bandwidths in excess of 350 Hz, but that bandwidths in excess of one to two kHz would offer diminishing advantage, independent of the higher antenna gains. This range of bandwidths can then be considered as a receiver design requirement.

5.4.6.5 Low Gain Antennas - Low gain antennas are required in the SL to radiate the Low Rate Radio output toward Earth and accept the DSN signals for the Command Receiver. This section discusses the rationale used in determining the antenna

SEARCH TIME VS ANGULAR SEARCH RANGE

Conditions: Worst-Case Link Budget

Incl. CMD Modulation

PLL Lock-On Probability = 99.9%

G = Antenna Gain

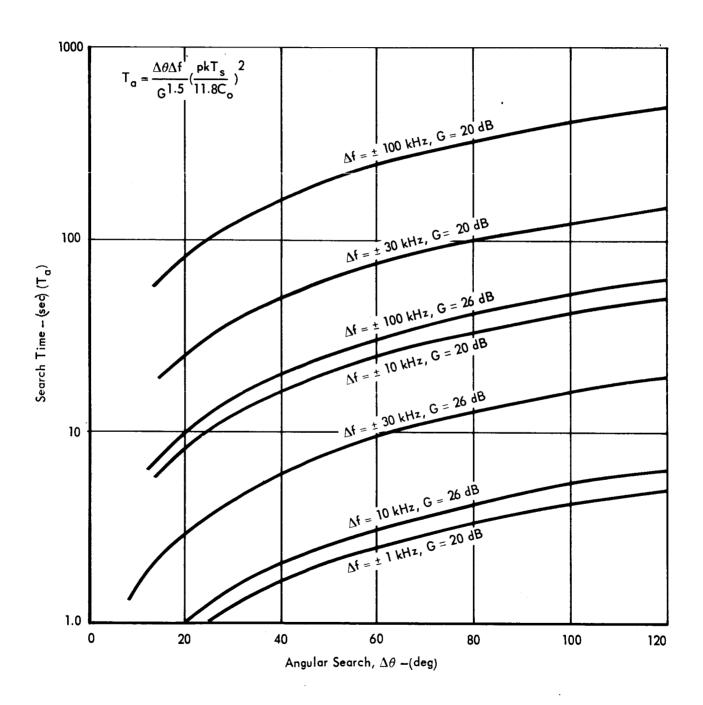


Figure 5.4-42 5.4-92

system configuration. The selected configuration consists of individual radiators for each link which are located on a deployable mast.

5.4.6.5.1 Requirements and Constraints - The design requriements and constraints for the Low Rate Telemetry and the Command Antenna system are identical since these functions are required primarily during the same portion of mission and since they are both direct links to Earth. The requirements and constraints of interest are as follows:

- o Provide essentially hemispheric radiation pattern coverage.
- o Operate from immediately after landing until the end of the mission during the periods the Earth is within view of the SL.
- o Operate from a non-leveled SL on surface slopes up to 34 degrees with a possible additional 5 degree slope induced by the crush of the CB impact attenuation material.
- o Provide radio frequency (RF) isolation of the Command Receiver from the Low Rate transmitter.
- o Operate in the event of failure of any SL deployables.
- o Provide protection against single point failures in both the Low Data Rate link and the Command link.

5.4.6.5.2 <u>Design Characteristics</u> - The Command and Low Rate Telemetry functions are the primary modes of access to the SL systems from Earth. The capability to provide these functions is therefore desirable over as much of the Earth view period as possible. The antenna location selection on the SL should therefore provide an unobstructed view over the complete hemisphere above the lander. This implies that the viewing obstructions of the SL deployable equipment, such as the High Gain Antenna and the experiment deployables, be minimized. The large size of the High Gain antenna parabolic dish and its location near the center of the SL would present a significant viewing obstruction for the low gain antennas if they were located on the top surface of the SL. For this reason the low gain antennas have been located on a laterally deployed mast. The lateral deployment also provides an unobstructed 360° degree view for the High Gain Antenna whereas a vertical deployment would not. The mast length required to provide a complete hemispheric view for the low gain antennas is prohibitive, and a compromise on mast length is necessary. A 66 inch length was selected and, when the mast is deployed from one corner of the SL, results in only a 20 degree section of the sphere obstructed when the High Gain antenna is in the worst case position. This length provides an unobstructed view for the low gain antennas of 120 degrees solid angle, (\pm 60 degrees from Lander vertical).

5.4.6.5.3 Antenna Deployment — The deployment of the boom can be accomplished by telescoping or rotating. The deployment mechanism has considerable impact on the antenna transmission line requirements since the line must survive the deployment cycle. Telescoping mechanisms require either a flexible cable wound around the telescoping mast or a spool to feed the cable down the mast during deployment. Both approaches require the use of flexible cable which can be significantly affected by the environment. The rotating mast will allow use of semi-rigid cable along the length of the mast, with a relatively short length of flexible cable around the rotation point. Semi-rigid cable also provides lower RF losses. These reasons contributed to the selection of a rotating mechanism.

5.4.6.5.4 <u>Design Alternatives</u> - The Low Rate Radio transmitter and the Command Receiver frequencies are 2292 Mhz and 2113 MHz respectively. A single radiator of the frequency independent type (spirals, log periodic, etc.) would provide the proper radiation pattern coverage over this frequency range when located on a deployable mast. However, a single radiator requires a diplexer (with its insertion loss) to separate the combined transmitter and receiver frequencies. The single radiator also presents a failure mode whereby both the Low Rate link and the Command link could be lost with a single failure. A two radiator approach eliminates the requirement for the diplexer since adequate RF isolation of the Command Receiver from the Low Rate transmitter can be obtained by physical separation; it also eliminates the single failure mode described above. Therefore, individual antennas are used for the Low Rate telemetry and the Command links.

It is desirable to minimize the number of masts required on the SI. The two antennas are therefore located on a common mast which also has the Remote Detector of the Spectro-Radiometer and the Atmospheric Package mounted on it. The mast is stowed on the top surface of the SL opposite the High Gain Antenna. This minimizes the field-of-view obstruction presented by the stowed High Gain antenna in the event the Low Gain antenna mast does not deploy. In the stowed condition the antennas are maintained in a position which orients the radiation pattern along an axis normal to the top surface of the SL. Upon deployment this orientation is maintained.

It would be desirable to orient the antennas to the Mars local vertical in order to minimize the radiation pattern coverage requirements. The worst case view angles to Earth occur when the 34 degree surface slope is oriented in a North-South direction and the impact material crush angle is directly additive to give a 39 degree maximum tilt with the local vertical. For a 10 degree North

latitude landing and a 16.5 degree South Sub-Earth latitude (4 February 1974), the worst case view angle is 65.5 degrees from the lander vertical. For a 40 degree South landing latitude and a 2 degree North Sub-Earth latitude (22 April 1974), the worst case view angle is 81 degrees. Considering the small probability that 34 degrees slopes do indeed exist on Mars and also that a landing will occur on such a slope which has an unfavorable azimuth orientation, it is rationalized that the added complexity of a leveling mechanism is not warranted, and an antenna pattern which provides at least OdB gain over the unobstructed 120 degree solid angle is satisfactory.

5.4.6.5.4 Antenna Selection - Antenna types investigated and tested for applicability to the VOYAGER mission included crossed dipoles, short helixes, open ended circular waveguide and flat sprials. All of these present essentially 80 degree 3dB beamwidth, symmetrical radiation patterns. However, the dipoles are narrow band, and could suffer from detuning in the Mars environment. Open ended waveguide would require more volume than the spiral or helix, with no improvement in performance. The cavity backed Archimedes spiral presents a more symmetrical pattern than the short helix, with a smaller axial ratio for angles off axis.

5.4.6.5.6 Conclusion - Individual low gain transmit and receive antennas provide excellent RF isolation between signal paths, and eliminate the possibility of a common electrical failure point. A deployable mast, oriented to point the antennas along lander vertical, provides sufficient unobstructed field of view. Cavity backed Archimides spirals provide adequate pattern coverage, circular polarization, and bandwidth sufficient to avoid the possibility of environmental detuning. The preferred design for the low gain antennas is therefore, two

cavity backed Archimedes spirals mounted on a deployable mast.

- 5.4.7 <u>Radio Subsystem</u> The Radio Subsystem for the SL consists of the High Rate Radio transponder, the Low Rate transmitter, and the Tracking Receiver for the High Gain Antenna. The latter is discussed in Section 5.4.6.4. The High Rate and Low Rate components are discussed in the following sections.
- 5.4.7.1 <u>SL High Rate Radio</u> The SL high rate radio transponder, with a low gain antenna receives the command signal from the DSIF. Because of the two way Doppler tracking requirement, the transponder must be completely phase coherent, this is achieved through the use of a phase-locked transponder. The threshold sensitivity of the phase coherent transponder is characterized by the automatic phase control (APC) loop threshold noise bandwidth (2B_{Lo}) as well as receiver noise figure. For the Mariner 69 Flight Spacecraft radio transponder the APC loop threshold noise bandwidth is 20 Hz and the command carrier sensitivity is -147 dBm with a 9 dB receiver noise figure. For the VOYAGER SL High Rate Radio, however, the required threshold sensitivity 1s -150 dBm which requires the receiver noise figure be kept under 6 dB if the APC loop bandwidth is 20 Hz.

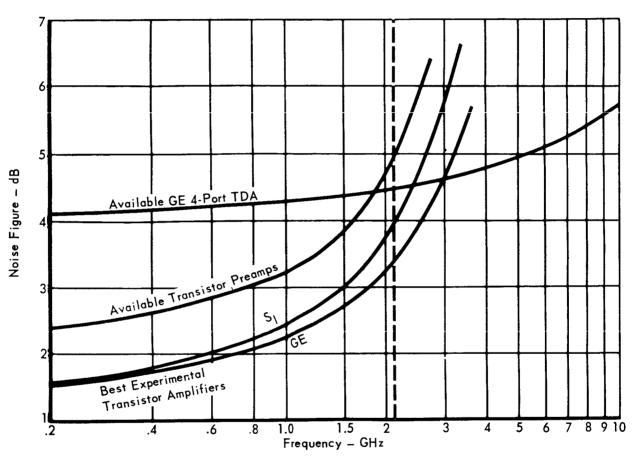
The required low noise characteristics can be obtained with any of the following devices.

- a. tunnel diode amplifier (TDA)
- b. transistor amplifier
- c. low noise traveling wave tube
- d. parametric amplifier
- e. maser

The last three devices have low efficiency, complex circuitry and low reliability, leaving the tunnel diode and transistor S -band amplifiers for consideration (See Figure 5.4-43). Because of the heat sterilization requirement, germanium devices cannot be used. No data have yet been obtained from a silicon tunnel-diode amplifier but noise is estimated to be greater than 5 dB. Silicon transistor S-band preamplifiers in the experimental stage have a noise figure of 4 dB at 2.1 GH. The sterilization restraint, therefore, imposes a state-of-the-art development in the high rate S-band amplifier, with the silicon-transistor amplifier being the preferred approach.

An alternative is to reduce the APC loop noise bandwidth. This is also a development task since it involves major modification of the Mariner 69 Flight Spacecraft Radio APC loop design including providing a larger capacitor in the loop filter and a more stable VCO. While this development can be accomplished within the program schedule, the preferred approach is to reduce the receiver noise figure

A COMPARISON OF TDA TRANSISTOR PREAMP NOISE FIGURES



as discussed in the previous paragraph. This approach was chosen because it has less impact on transponder design, and faster acquisition time, since the 20 Hz bandwidth is used.

5.4.7.2 <u>SL Low Rate Radio</u> - The most significant considerations in the SL Low Rate Radio design are the method of MFSK signal generation and the power amplification technique.

MFSK Signal Generation - The signals required for the Low Rate Radio are sixteen keyed tones centered about a nominal carrier frequency of 2292 MHz with a spacing of 6.25 Hz between them. The short term stability for each tone must be less than + 0.23 Hz as discussed in Section 5.4.3.4.

The tones are generated at some low frequency and must be either multiplied or translated to the 2292 MHz carrier frequency. Frequency translation is preferred to multiplication in order to preserve the stability of the tone spacing and allow the tones to be generated with grater spacing. However, multiplication by two is used after the power amplifier as discussed in the next section.

The tones may be generated by a frequency synthesizer or a voltage controlled crystal oscillator (VCXO). A frequency synthesizer has been selected because of its inherent tone spacing stability.

The total stability requirement at S-band requires that the crystal oscillator in the frequency translator be enclosed in an oven which regulates the crystal temperature within 0.01 °C. The oscillator then exhibits a short term stability of 1×10^{-11} per one second average and a long term stability of $\pm 5 \times 10^{-7}$ per year.

<u>S-Band Power Amplification</u> - Amplification of S-band frequencies with 5 watts of power output can be accomplished with a traveling wave tube (TWT), planar triode cavity amplifier or a solid state device. The solid state device was selected since it avoids the use of high power supply voltages, is resistant to vibration and exhibits greater potential reliability. A trade summary which led to the selection of the transistor amplifier and varactor multiplier for the baseline is shown in Figure 5.4-44.

The power handling capability of transistors is about 2 watts at 2.0 GHz. However beyond this frequency the power drops rapidly. The preferred method for achieving a 5 watt MFSK signal at 2.3 GHz is to generate the MFSK frequencies with one-half the required spacing at 1.15 GHz, then amplify the signal level up to 10 watts. The 10 watt 1.15 GHz signal will then be multiplied by a varactor doubler to obtain the 5 watt 2.3 GHz MFSK signal.

SLS LOW RATE RADIO POWER AMPLIFIER (f = 2293 MHz)

ALTERNATIVES FUNCTIONAL REQUIREMENTS	-	2	3	4	SELECTION
Amplifier S-Band Power to Obtain 5 Watt Output	TWT Amplifier (27 dB)	Planar Triode Cavity Amplifier (10 dB)	Transistor Amplifier	Transistor Amplifier & Varactor Multiplier	4
Simplicity Amp Pwr Sup	Simple Complex	Simple Complex	Complex Simple	Less Complex Simple	4
Volume Amp (cu in.) Pwr Sup	20 20	19 20	25 16	20 16	4
Weight Amp (1b) Pwr Sup	- е	3	1.5 0.8	1.1 0.8	4
Efficiency	25%	25%	%07	21%	1 or 2

5.4.8 Telecommunication Link Analysis — In the preceding sections we have summarized the rationale leading to selection of the preferred design. In this section we will present a summary performance analysis, and show the requirement and capabilities for telemetering data and receiving command instructions. The telecommunication links have been designed for direct Surface Laboratory (SL) to Earth communications, and are compatible with the planned DSIF capabilities for 1973. The anticipated DSIF parameters used in this analysis are summarized in Figure 5.4-45. 5.4.8.1 SLS Telecommunication Link Characteristics — Three links are provided: a high-rate telemetry link, a command link, and a low-rate link. The high-rate link is used for primary mission data transmission at a rate of up to 30 x 10⁶ bits per day and, in a degraded mode, at least 5 x 10⁶ bits per day. The command link is a JPL standard two-channel system, employing PN synchronization on a square wave subcarrier and transmitting data on a sine wave subcarrier. The backup low-rate link transmits engineering data at a 0.5 bps data rate.

The high-rate link provides a PSK/PM carrier at a 20 watt output for exciting a 24 dB gain mechanically steered antenna. Convolutional encoding with sequential decoding increases the link efficiency. The primary data input to this link is from the data storage subsystem, which permits choice of transmission bit rates that are not dependent on accumulation rates. Bit rates in the high rate link are selectable, on command, to be 300, 600, or 1200 bps, depending on the accuracy with which the antenna is aligned and the amount of data remaining in the storage subsystem. The transmitter frequency is normally controlled by a precision crystal oscillator; however, a transponder mode is available to permit coherent, two-way Doppler tracking when the command receiver is locked-up.

The command link employs a two-channel PSK/PM, coherent phase-lock-loop receiver with a low-noise preamplifier. The command bit rate has been specified as 1 bps.

A noncoherent 16-FSK 5-watt S-band transmitter, operating into a low-gain antenna, provides a backup low-rate link. This link requires a special receiver at the DSIF stations (See paragraph 5.4.3.4). An additional receiving link is provided by the tracking receiver, which generates antenna steering error signals for the Control Subsystem.

The link analyses are based on the 1973 launch and arrival trajectories. The nominal operating range is 2.5×10^8 km with a maximum of 2.85×10^8 km. The SL circuit losses are shown in Figure 5.4-46. All three links assume the use of the 210-ft. DSIF antenna, with 45°K noise temperature and 10 KW command transmitter power.

DSIF PARAMETERS

	RECEIVE	TRANSMIT	REFERENCES
Ground Transmitter Power			
Present Capability Planned Capability		10 kW ± 0.5 dB	EPD 283 Rev. 2
(Goldstone Venus Station Now)		100 kW ± 0.5 dB	EPD 283 Rev. 2
Ground Circuit Loss 210-foot Diplexed, Non-Tracking Feed 210-foot Diplexed and Tracking Feed		-0.2 ± 0.1 dB -0.4 ± 0.1 dB	TM 33-83 R1 EPD 283
210-foot Maser	-0.2 ^{+0.1} dB		EPD 283
210-foot Paramp 85-foot Diplexed and Tracking Feed	-0.3 ± 0.1 dB	-0.4 ± 0.1 dB	EPD 283 EPD 283
85-foot Maser	-0.2 ^{+0.1} _{-0.0} dB		EPD 283
85-foot Paramp Acquisition Antenna	-0.3 ± 0.1 dB -0.5 ± 0.2 dB		EPD 283 MC-4-310A
Ground Antenna Gain		7	
210-foot	61.0 ± 1.0 dB	60.0 ± 0.8 dB	EPD 283 Rev. 2
85-foot	53.0 ^{±1.0} / _{-0.5} dB	51.0 ^{+1.0} dB	EPD 283 Rev. 2
Acquisition Antenna	22 ± 1 dB	19.1 ± 1 dB	EPD 283 Rev. 2
Antenna Pointing Loss			
210-foot	-0.1 ± 0.1 dB	-0.1 ± 0.1 dB	EPD 283 (1)
85-foot	-0.0 ^{+0.0} dB	-0.0 ^{+0.0} dB	EPD 283 (1)
Polarization Loss			
210-foot 85-foot	0.8 dB Maximum 0.7 dB Maximum		EPD 283 Rev. 2 EPD 283 Rev. 2
System Noise Temperature			
210-foot Diplexed with Maser (2) 85-foot, Diplexed with Maser (2)	45° ± 10°K 55° ± 10°K		EPD 283 Rev. 2 EPD 283 Rev. 2

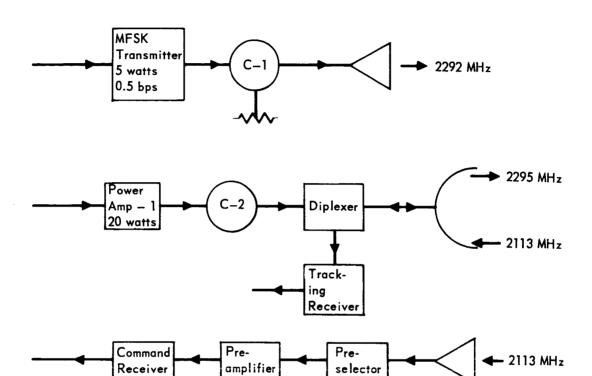
Notes:

(1) Computed from 0.02-degree angle error.

(2) For 10 kW transmitter power; low-noise reception with high power (100 kW) is still under development.

Figure 5.4-45

S-BAND SL RADIO SUBSYSTEM



C = Circulator Switch

CIRCUIT LOSSES - dB

	Low Rate Transmitter	High Rate Transmitter	Low Gain Receive	High Gain Receiver
Circulator Switch	-0.2 + 0.0 -0.2	-0.2 + 0.0 - 0.2		
Diplexer		-0.3 + 0.1 - 0.1	-0.5 + 0.1 - 0.1	
Preselector				-0.9 + 0.1 -0.1
Cable	-0.6 + 0.0 -0.2	-0.8 + 0.0 -0.2	-0.8 +0.0 -0.2	-0.6 + 0.0 -0.2
Total	-0.8; +0.0, -0.4	-1.3; +0.1, -0.5	-1.3; +0.1, -0.3	-1.5; +0.1, -0.3

These analyses are not particularily sensitive to planned landing site latitude or longitude; however, unanticipated deviations in landing site can affect the low-rate link receiver frequency tracking circuits. An uncertainty of \pm 500 km provides more frequency (uncorrectable Doppler) rate than anticipated from the oscillator short term stability, and, in fact, specifies the minimum power required to achieve and maintain frequency-lock in the receiver.

5.4.8.2 <u>High Rate Telemetry Link Analysis</u> - A summary of this link analysis is presented in Figure 5.4-47. A high-rate-link transmitter power of 20 watts was considered a conservative maximum power for a sterilizable, high-efficiency TWTA, and is well below the anticipated breakdown power level at the antenna feed. The ± 0.6 dB tolerance was chosen rather arbitrarily, and is subject to review during the development phase.

Figure 5.4-46 presents a summary diagram of the anticipated transmitter circuit losses. Although the TWTA is remote from the antenna feed, the line losses are minimized by use of low-loss, solid jacket coaxial cables wherever practical, particularly through the long section of the high-gain antenna mount. Refer to Section 5.1, Part C, for a description of the antenna mount and feed. The transmitting antenna gain is a compromise between a maximized transmission rate where all systems are operating, and maintenance of usable gain for degraded modes where pointing errors increase.

In the normal sequence of events, the antenna is erected, and the hour axis is oriented nearly parallel to the polar axis of Mars. Subsequently, there is a programmed rotation about the hour and declination axes to point the antenna toward Earth. If all systems are within normal operational boundaries, the antenna pointing error will be less than 6 (3 σ); and if a command carrier is present, the tracking receiver will acquire lock and cause the control system to adjust the antenna hour and declination axes to reduce the error to less than ± 1 . The pointing error loss for this mode is therefore not more than 1.1 dB. In any contingency mode where autotrack is used, the same steering error and pointing error loss is applicable. If the autotrack mode is inhibited, or otherwise not available, the antenna pointing loss increases to 4.4 dB. Although this is a contingency mode of operation, the sequencer and timer will normally command the 300 bps data rate, which is commensurate with this mode, until over-ridden by direct command or until a locked-and-tracking signal is received from the tracking receiver. The intermediate 600 bps

TELECOMMUNICATION DESIGN CONTROL

CHANNEL: SURFACE LABORATORY - EARTH, HIGH RATE, PSK/PM, TELEMETRY MODE: SLS; HIGH GAIN, 20W; DSIF: 210 FT, MASER PREAMPLIFIER, CLOCK TRACK

	PARAMETER	VALUE	TOLERANCE (dB)	SOURCE
1	Total Transmitter Power (20 watts)	42.7 dBm	+0 6 -0.6	5. 4.8. 1
2	Transmitting Circuit Loss	–1.3 dB	+0.3 -0.3	5.4.8.1
3	Transmitting Antenna Gain	24.3 dB	+0.0 -0.5	5.4.8.1
4	Transmitting Antenna Pointing Loss	0.0 dB	+0.0 -4.4	5.4.8.1
5	Space Loss (2295 MHz, 2.5 x 10 ⁸ Km)	-267.7 dB	+0.0 -1.2	Calculated
6	Polarization Loss	-0.1 dB	+0.1 -0.4	5.4.8.2
7	Receiving Antenna Gain	61.0 dB	+1.0 -1.0	5.4.8
8	Receiving Antenna Pointing Loss	-0.1 dB	+0.1 -0.1	5.4_8
9	Receiving Circuit Loss	Included in	Line 7	
10	Net Circuit Loss	- 183.9 dB	+ 1.5 -7.9	Σ Lines 2 to 9
11	Total Received Power	-14 1.2 dBm	+2.1 -8.5	Lines 1 + 10
12	Receiver Noise Spectral Density			5.4.8
	(N/B) (T System = 45 ± 10 °K)	– 182. 1 dBm/Hz	+0.9 -1.1	
13	Carrier Modulation Loss			
14	Received Carrier Power	-7.7 dB	+0.8 -0.8	Calculated
15	Carrier APC Noise Bandwidth (2B _{LO} = 5 Hz)	– 148.9 dBm	+2.9 -9.3	Lines 11+13
	CARRIER REPEORMANCE TRACKING (O W)	7.0 dB/Hz		5.4.8.2
14	CARRIER PERFORMANCE - TRACKING (One-Way)	0.0 dB		
16	Threshold SNR in 2B _{Lo}			
17	Threshold Carrier Power	-175.1 dBm	+0.9 -1.1	Lines 12+15+16
18	Performance Margin	26.2 dB	+4.0 -10.2	Lines 14-17
	CARRIER PERFORMANCE - TRACKING (Two-Way)			
19	Threshold SNR in 2BL	2.0 dB	+1.0 -1.0	
20		172 1 40	10 01	10 15 10
20	Threshold Carrier Power	– 173. 1 dBm	+ 1.0 -2.1	Lines 12+15+19
21	Performance Margin	24.2 dB	+ 5.0 - 11.2	Lines 14-20
1 1	CARRIER PERFORMANCE			
22	Threshold SNR in 2BL	16.0 dB		5.4.8.2
23	Threshold Carrier Power	-1 <i>5</i> 9.1 dBm	+0.9 -1.1	Lines 12+15+22
24	Performance Margin	10.2 dB	+ 4.0 - 10.2	Lines 14-23
	1 errormance margin	10.2 0.0	""	211103 14 20
	DATA CHANNEL			
25	Modulation Loss	-0.8 dB	+0.2 -0.2	Calculated
26	Received Data Subcarrier Power	-142.0 dBm	+2.3 -8.7	Lines 11+25
27	Bit Rate (1/T) 300 bps	24.8 dB/Hz		
28	Required ST/N/B	2.9 dB	+0.1 -0.0	5.4.8.2
29	Threshold Subcarrier Power	-154.4 dBm	+1.0 -1.1	Lines 12+27+28
30	Performance Margin	12.4 dB	+3.4 -9.7	Lines 26-29
	SYNC CHANNEL			
31	Modulation Loss			
32	Received Sync Subcarrier Power			
33	Sync APC Noise Bandwidth (2B _{LO} = Hz)			
34	Threshold SNR in 2B _{LO}			
35	Threshold Subcarrier Power			
36	Performance Margin			

Figure 5.4-47

rate is provided upon command if sufficient signal strength is available. The 1200 bps rate is normally used only in autotrack, although command selection is also possible. Figure 5.4-48 shows a Design Control Table for the 1200 bps autotrack mode.

The space loss has been calculated for the nominal 1.67 Astronautical Unit (AU) (2.5 x 10^8 km) range. A 1.2 dB negative tolerance has been added to account for the range increase up to 1.90 AU (2.85 x 10^8 km) at the latest anticipated landing date. Refer to Volume II, Part B, Section 2.2 for a discussion of trajectory and arrival date constraints.

The polarization loss, line 6 of Figure 5.4-47, accounts for an estimated 3 dB axial ratio 6° off beam center. The nominal value reflects essentially 0 dB axial ratio for the DSIF antenna, while the tolerance allows up to 3 dB axial ratio.

Use of square wave subcarrier modulation results in a choice of modulation index of 1.15 radians, which yields a 7.7 dB carrier modulation loss. The tolerances are based on a linear phase modulator and a ± 4% input voltage tolerance. Although a 5 Hz carrier APC noise bandwidth is assumed for 1973, a possibility exists that a 1 Hz bandwidth may become available. For this link, however, reduction of carrier power below the chosen level would introduce more severe modulation—stability. requirements and would increase the data channel power very little. The modulation index has been chosen for the 300 bps data rate and is maintained constant for the other data rates to minimize complexity.

Selection of a threshold SNR in 2 B_{LO} is complicated because degradation suffered by a sequential decoder resulting from a noisy phase reference has thus far eluded complete analysis. Laboratory results based on a simulation by Haccound (See Reference 5.4-20) have indicated the following:

SNR in 2 B _{LO}	Degradation (without interleaving)
13 dB	1.0 dB
16 dB	0.5 dB
19 dB	0.1 dB

We chose the value of 16 dB, and allowed the 0.5 dB degradation margin, even though interleaving is employed to minimize the probability of decoder hang-up due to associated bit errors.

The required data threshold is defined as the energy-to-noise spectral density (ST/N $_{
m O}$) required at the input to the subcarrier demodulator for a specified bit

5.4 - 105

TELECOMMUNICATION DESIGN CONTROL

CHANNEL: SURFACE LABORATORY - EARTH HIGH RATE, PSK/PM, TELEMETRY MODE: SLS, HIGH GAIN 20W; DSIF: 210 FT, MASER PREAMPLIFIER, AUTOTRACK

NO.	PARAMETER	VALUE	TOLERANCE (dB)	SOURCE
1	Total Transmitter Power (20 watts)			
2	Transmitting Circuit Loss			
3	Transmitting Antenna Gain			
4	Transmitting Antenna Pointing Loss		-1.1	-
5	Space Loss (2295 MHz, 2.5 x 10 ⁸ Km)			-
6	Polarization Loss			
7	Receiving Antenna Gain			
8	Receiving Antenna Pointing Loss			
9	Receiving Circuit Loss			
10	Net Circuit Loss		-4.6	†
11	Total Received Power		-5.2	†
12	Receiver Noise Spectral Density (N/B) (T System = 45 ±10 °K)			
13	Carrier Modulation Loss			
14	Received Carrier Power		-6.0	
15	Carrier APC Noise Bandwidth (2BLo = 5 Hz)		5.0	
	CARRIER PERFORMANCE - TRACKING (One-Way)			
16	Threshold SNR in 2BLo			
17	Threshold Carrier Power			
18	Performance Margin		6.9	
19	CARRIER PERFORMANCE - TRACKING (Two-Way)			
19	Threshold SNR in 2BLo			
20	Threshold Carrier Power			
21	Performance Margin		-7.9	
	CARRIER PERFORMANCE			
22	Threshold SNR in 2BLo			
23	Threshold Carrier Power	<u> </u>		
24	Performance Margin	·	-6.9	,
	DATA CHANNEL			
25	Modulation Loss			
26	Received Data Subcarrier Power		-5.4	
27	Bit Rate (1/T) 1200 bps	30.8 dB-Hz		
28	Required ST/N/B			
29	Threshold Subcarrier Power	-148.4 dBm	+1.0 -1.1	
30	Performance Margin	6.4 dB	+3.4 -6.4	
	SYNC CHANNEL			
31	Modulation Loss			
32	Received Sync Subcarrier Power			
33	Sync APC Noise BW (2B _{Lo} = Hz)			
34	Threshold SNR in 2BLo			
35	Threshold Subcarrier Power			
36	Performance Margin			

COMMENTS:

Figure 5.4-48

error rate. The required data threshold includes losses due to carrier and sub-carrier demodulators, bit synchronization, imperfect coding, filters, etc. The various losses are summarized in Figure 5.4-49 and are discussed in Section 5.4.2. The theoretical data threshold is -1.6 dB.

Due to the high data rates compared to the synchronization channel noise bandwidth, no additional power is required for synchronization. Bit synchronization and subcarrier demodulation can be readily accomplished with either a squaring loop or the special bit synchronizer developed for the Capsule Bus relay link.

The net data channel performance margin as shown on line 30 of Figure 5.4-47 is nearly sufficient to permit operation of 600 bps in the clock track mode: hence a 600 bps mode is available on command. The performance margin in the autotrack mode is less conservative, but adquate.

5.4.8.3 Low Rate Telemetry Link Analysis – A summary of this link analysis is presented in Figure 5.4-50. The transmitter power of 5 watts was chosen to provide enough power for reception and frequency tracking by the DSIF and also to enable the use of a solid-state transmitter and low-gain antenna. The \pm 0.5 dB tolerance is subject to review during the development phase.

The anticipated transmitter circuit losses are shown in Figure 5.4-46. Separate low gain antennas are used for the low-rate transmitter and command receiver to eliminate diplexer losses.

The transmitting antenna provides a gain greater than 0 dB over a 120° solid angle. The 1 dB negative tolerance is included to provide coverage over a 140° solid angle in case ground slopes permit communications up to 70° from normal to the SL.

The space loss has been calculated for the nominal 1.6 AU (2.5 x 10^8 km) range. A 1.2 dB negative tolerance has been added to account for arrival at the latest anticipated landing date when the range is 1.90 AU (2.85 x 10^8 km).

The nominal value of polarization loss accounts for communications near the axis of the transmitting antenna and allows for up to 1.5 dB axial ratios for both transmitting and receiving antennas while the negative tolerance applies at the edges of the transmitting antenna pattern.

The 16-FSK modulation at a data rate of 0.5 bps allows noncoherent reception. This precludes the need for power to maintain channel coherence and increases the efficiency of the link. Sixteen tones were chosen as a compromise between the higher efficiency of a large number of tones and the difficulties associated with time synchronization of tones with long duration. The low-rate receiver and the

REQUIRED ST/ $_{\mbox{N/B}}$ FOR MODEL DEGRADATION, dB

	WITHO	OUT INTERLEAVING		WITH INTERLEAVING
SOURCE OF DEGRADATION	$\left(\frac{s}{N}\right)_{2B_{Lo}} = 13 \text{ dB}$	$\left(\frac{S}{N}\right)_{2B_{Lo}} = 16 \text{ dB}$	$\left(\frac{S}{N}\right)_{2B_{Lo}} = 19 \text{ dB}$	$\left(\frac{S}{N}\right)_{2B_{Lo}} = 13 \text{ dB}$
a = 1	3.0	3.0	3.0	3.0
Q = 8	0.2	0.2	0.2	0.2
V = 3	0.6	0.6	0.6	0.6
a>1	0.14	0.14	0.14	0.14
Sym and Tail	0.06	0.06	0.06	0.06
Incoherence	1.0	0.5	0.1	0.1
Total Loss, dB	5.0	4.5	4.1	4.1
Required ST/ _{N/B}	3.4	2.9	2.5	2.5

TELECOMMUNICATION DESIGN CONTROL

CHANNEL: SURFACE LABORATORY — EARTH, LOW RATE, MFSK, TELEMETRY MODE: SLS LOW GAIN, 5W; DSIF: 210 FT., MASER PREAMPLIFIER

NO.	PARAMETER	VALUE	TOLERA	NCE (dB)	SOURCE
ī	Total Transmitter Power (5 watts)	36.7 dBm	+ 0.5	-0.5	5.4.8.1
2	Transmitting Circuit Loss	-0.7 dB	+ 0.1	-0.1	5.4.8.1
3	Transmitting Antenna Gain	0.0 dB	+ 1.0	-1.0	5.4.8.1
4	Transmitting Antenna Pointing Loss	Included in Line	3		_
5	Space Loss (2295 MHz, 2.5 x 108 km)	-267.7 dB	+ 0.0	-1.2	Calculated
6	Polarization Loss	-0.1 dB	+ 0.1	-0.6	5.4.8.4
7	Receiving Antenna Gain	61.0 dB	+ 1.0	-1.0	5.4.8
8	Receiving Antenna Pointing Loss	-0.1 dB	+ 0.1	-0.1	5.4.8
9	Receiving Circuit Loss	-0.1 dB	+ 0.1	-0.1	5.4.8
10	Net Circuit Loss	-207.7 dB	+2.4	-4.1	Σ Lines 2 to 9
11	Total Received Power	-171.0 dBm	+ 2.9	-4.6	Lines 1 + 10
12	Receiver Noise Spectral Density (N/B) (T System = 45 ± 10 °K)	_182.1 dBm/Hz	+ 0.9	-1.1	5.4.8
13	Carrier Modulation Loss			,,,	• • • • • • • • • • • • • • • • • • • •
14	Received Carrier Power				
15	Carrier AFC Noise BW (2B _{Lo} = Hz)				
1	CARRIER PERFORMANCE - TRACKING (One-Way)				
16	Threshold SNR in 2B _{Lo}				
17	Threshold Carrier Power				
18	Performance Margin				
	CARRIED REDECRIVANCE TRACKING (T. W.)	:			
19	CARRIER PERFORMANCE – TRACKING (Two-Way) Threshold SNR in 2BL				
20	Threshold Carrier Power				
21	Performance Margin				
41	renomiance margin				
	CARRIER PERFORMANCE				
22	Threshold SNR in 2B _L _o			İ	
23	Threshold Carrier Power				
24	Performance Margin				
	•				
25	DATA CHANNEL Modulation Loss				
26	Received Data Subcarrier Power				
27	Bit Rate (1/T) 0.5 bps	-171.0 dBm	+ 2.9	-4.6	Line 11
28	Required ST/N/B ($P_{e} = 5 \times 10^{-3}$)	-3.0 dB-Hz			5.4.8.3
29	Threshold Subcarrier Power	8.1 dB	+ 0.5		5.4.8.3
30	Performance Margin	-177.0 dBm	+ 1.4		Lines 12 + 27 + 28
		6.0 dB	+ 4.0	-6.0	Lines 26-29
ا ۾ ا	SYNC CHANNEL			1	
31	Modulation Loss				
32	Received Sync Subcarrier Power			İ	İ
33	Sync APC Noise BW QB _{Lo} = Hz)				
34	Threshold SNR in 2B _{Lo}				
35	Threshold Subcarrier Power				
36	Performance Margin				

required value of ST/No are discussed in Section 5.4.3.4.

The low-rate performance margin is greater than or equal to zero, providing transmission of low-rate data using a 5-watt, solid-state transmitter and low-gain antenna. Thus a backup link, that does not exhibit the failure modes associated with a TWTA or a pointed antenna is provided for these data.

5.4.8.4 <u>Command Link</u> - The command link design control table shown in Figure 5.4-51 assumes the transmission parameters shown in Figure 5.4-45 and the receiving circuit losses of Figure 5.4-46. The receiving antenna is similar to that used for the low-rate data link.

The receiver system temperature is derived in Figure 5.4-52. The other receiver parameters are identical to those to be used in the Mariner '69 command receiver.

The modulation losses assume linear phase modulation with a deviation stability of \pm 2.5%. The form of modulation and synchronization is also identical to that used in the Mariner series in that a pseudo noise (PN) synchronization code is used and the command bits are modulated on a sinusoidal subcarrier. The only addition to the command structure is the Bose-Chaudhuri coding and the increased number and length of commands discussed in Section 5.4.5.

The net margin in the command link is sufficient to insure command capability throughout the mission.

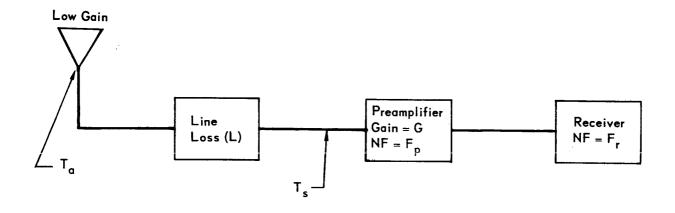
TELECOMMUNICATIONS DESIGN CONTROL TABLE

CHANNEL: EARTH - SURFACE LABORATORY, COMMAND MODE: SLS LOW GAIN, PREAMPLIFIER: DSIF: 210 FT., 10 KW

NO.	DADAMSTED		I		
NO.	PARAMETER	VALUE		NCE (dB)	
1	Total Transmitter Power (10,000 watts)	70.0 dBm	+ 0.5	-0.5	5.4.8.1
2	Transmitting Circuit Loss	-0.4 dB	+ 0.1	-0.1	5.4.8.1
3	Transmitting Antenna Gain	60.0 dB	+ 0.8	-0.8	5.4.8.1
4	Transmitting Antenna Pointing Loss	-0.1 dB	+ 0.0	-0.1	5.4.8.4
5	Space Loss (2113 MHz, 2.5 x 108 km)	−266.9 dB	+ 0.0	-1.2	5.4.8.3
6	Polarization Loss	-0.1 dB	+ 0.1	-0.6	5.4.8.3
7	Receiving Antenna Gain	+0.0 dB	+ 1.0	-1.0	5.4.8.3
8	Receiving Antenna Pointing Loss	Included in Line	7		-
9	Receiving Circuit Loss	_1.3 dB	+ 0.2	-0.2	5.4.8
10	Net Circuit Loss	–208.8 dB	+ 2.2	-4.0	Σ Lines 2 to 9
11	Total Received Power	–138.8 dB	+ 2.7	-4.5	Lines 1 + 10
12	Receiver Noise Spectral Density (N/B) (T System = 644 + 136 - 55°K)	–170.5 dBm/Hz	+ 0.8	-0.4	5.4.8.4
13	Carrier Modulation Loss	-2.4 dB	+ 0.3	-0.3	5.4.8.4
14	Received Carrier Power	-141.2 dBm	+ 3.0		Lines 11+13
15	Carrier APC Noise BW $(2B_{Lo} = 20 \text{ Hz})$	13.0 dB-Hz	+ 0.0		5.4.8.4
16	CARRIER PERFORMANCE - TRACKING (One-Way) Threshold SNR in 2B _{Lo}				
17	Threshold Carrier Power				
18	Performance Margin				
	CARRIER PERFORMANCE - TRACKING (Two-Way)				
19	Threshold SNR in 2B _{Lo}	3.8 dB			5.4.8.4
20	Threshold Carrier Power	-153.7 dBm	+ 0.8	-1.4	Lines 12 + 15 + 19
21	Performance Margin	12.5 dB	+4.4	-5.6	Lines 14-20
	-				
	CARRIER PERFORMANCE				
22	Threshold SNR in 2B _{Lo}	8.0 dB	+ 1.0	-1.0	5.4.8.4
23	Threshold Carrier Power	-149.5 dBm	+ 1.8	-2.4	Lines 12 + 15 + 22
24	Per formance Margin	8.3 dB	+ 5.4		Lines 14-23
	DATA CHANKE				
25	DATA CHANNEL Modulation Loss	_8.5 dB	+ 0.2	-0.2	5.4.8.4
26	Received Data Subcarrier Power				-
26		-147.3 dBm	+ 2.9		Lines 11 + 25
	Bit Rate (1/T) 1 bps	0.0 dB-Hz	1.0		5.4.8
28	Required ST/N/B	15.7 dB	+ 1.0		5.4.8.4
29	Threshold Subcarrier Power	-154.8 dBm	+ 1.8	-1.4	Lines 12 + 27 + 28
30	Performance Margin	7.5 dB	+ 4.3	-6.5	Lines 26-29
	SYNC CHANNEL				
31	Modulation Loss	-5.5 dB	+ 0.2	-0.3	5.4.8.4
32	Received Sync Subcarrier Power	-144.3 dBm	+ 2.9	-4.8	Lines 11 + 31
33	Sync APC Noise BW (2B _{Lo} = 2Hz)	+3.0 dB-Hz			5.4.8.4
34	Threshold SNR in 2B _{Lo}	+15.7 dB	+ 1.0	-1.0	5.4.8.4
35	Threshold Subcarrier Power	-151.8 dBm	+ 1.8	-1.4	Lines 12 + 33 + 34
36	Performance Margin	7.5 dB	+ 4.3		Lines 32-25

Figure 5.4-51

SYSTEM NOISE - TEMPERATURE MODEL



	L (dB)	T _a /L	$\left(\frac{L-1}{L}\right)$ TL	F _p (dB)	(F _p -1) T _o	G (dB)	F _r (dB)	$\left(\frac{F_{r}-1}{G}\right) T_{o}$	T _s
Worst	1.5	0°K	93°K	5.0	625°K	13	7.7	71 ° K	780°K
Nominal	1.3	0°K	78°K	4.5	528°K	15	7.1	38°K	644°K
Best	1.1	0°K	73°K	4.3	490°K	17	7.1	34°K	589°K

5.4.9 <u>Data Handling System Configuration</u> - Studies of the telemetry and science data subsystems requirements and the alternate configurations have been performed. We have studied the entire Data Handling Subsystem (DHS) as a functional entity in order to conduct these studies. The DHS encompasses the Science Data Subsystem (SDS), the Telemetry Subsystem (TM), and the Data Storage Subsystem (DSS). In those studies we have organized the data inputs, control outputs, and the flow paths into and out of the combined telemetry and science data subsystems. The functional interfaces with the data storage subsystem and the radio subsystem have been examined.

Based on the results of the functional requirements and external interface studies, the internal functions are analyzed, and an interface between the telemetry and science data subsystems is determined. Subsequent investigation was performed to determine the optimal implementation techniques for each of these subsystems.

From these studies we have evolved a stored program telemetry subsystem which provides control of the science data subsystem elements, the remote interface units, and controls the accumulation of data and the functions of the data storage subsystem. The preferred approach implementation is discussed in Section C 7.

5.4.9.1 Summary - Data are accumulated at low rates for most of the mission.

During launch through landing, the SL subsystems are essentially dormant, with only a brief period of activity during in-flight checkout. A cruise commutator is provided to monitor the SL subsystems status during the dormant phases, and operates under the control of the Capsule Bus telemetry subsystem. During in-flight checkout and landed operations, the SL telemetry and Science Data subsystems control the accumulation and transmission of data.

In the landed operation phase, two predominant data accumulation modes are encountered. Engineering and some of the science data are accumulated on a continuous periodic basis during the entire landed operation. The atmospheric properties experiments tend to be continuous in nature, requiring measurements of wind velocity and atmospheric temperature on a periodic basis, with increased sampling rates during sunrise and sunset. The other portion of the science data is accumulated in bursts. Panoramic imaging data is a prime example of burst type data, where a single low resolution image is obtained in four minutes, and consists of 2.16×10^6 bits of data.

A mixture of formats is desirable to cope with the variable nature of the data accumulation modes. The engineering data are organized in an interlaced tube format, while the science data are organized in a burst tube format, i.e., the collection of all of the samples in the tubes simultaneously rather than sequentially. All data to be transmitted on the high rate link should be accumulated in the data storage subsystem, and transmitted in a "last in - first out" manner. This accumulation of data in the data storage subsystem tape recorder is under the control of the telemetry subsystem. The imaging data is recorded directly, while all other data is accumulated in a telemetry buffer prior to recording.

The interface between the telemetry and science data subsystems is defined herein. The Science Data Subsystem provides the experiments sequencing instructions, accepts, processes and delivers the resulting data to the telemetry subsystem. The TM commands experiment measurements and controls data flow into the buffer accumulator and the data storage subsystem. The TM also provides the clock and data rate controls to the SDS.

The TM contains an electrically alterable stored program which controls its functions during the landed operations. The programmer employs a hardwired program with core-storage for gating, formatting, and experiment measurement control instructions.

The SDS is composed of nine remote interface units (RIU) physically packaged together on a common base. There is an RIU for each experiment, and the RIU contains the circuitry to sequence the associated science instrument in response to a measurement command. Each RIU also conditions, converts, and processes the resulting data output as required, and provides multiplexing and output controls. The RIU output data is distributed either to the telemetry or data storage subsystem.

5.4.9.2 <u>Requirements</u> - The DHS data requirements are specified by the data instrumentation List, Figure 5.4-4, and by the experiment time lines, Figure 5.4-5.

In conjunction with the data collection requirements, the DHS must also be compatible with the data transmission requirements and constraints specified in Section 5.4. All of these DHS requirements may be categorized as either data flow or data control requirements.

Data Flow Requirements - The data flow requirements have two principal facets: the data character and the data occurrence variability. Engineering or housekeeping data is characterized by a modest accuracy requirement and a ready availability for transmission. Scientific data on the other hand may either have modest accuracy requirements, or extreme accuracy requirements, and may or may not be readily available for transmission. For example, the alpha spectrometer outputs are discrete 256 bit words available only after, either a two hour (background count) or, an eight hour (prepared sample) operation. The scientific atmospheric properties experiments are continuously available, and only eight bits of data are collected per sample.

The engineering data may be termed "routine" data and can be conveniently formatted (grouped) into modes of operation, landed day and landed night. The science data may also be grouped into periodic science data or aperiodic science data. The periodic science data collected in a clearly identifiable routine, and usually accumulates modest amounts of data. The "day/night" mode occurs when the instruments are energized once every 15 minutes. The "sunrise/sunset" mode occurs when the instruments are energized once each minute. During each mode only eight bits per sample are taken. Aperiodic science is characterized by the lack of periodicity in the collection scheme, and the massive accumulation of bits per measurement. For example, two 2.16 x 10^6 bit television pictures are planned to be taken in the "morning", and five 0.96 x 10^6 bit television pictures in the "afternoon".

In addition to the character of the data (accuracy and collection rates) the collection periods are also variable. The collection periods are generally also related to the local time of day although some will be programmed in absolute time from touchdown. The television pictures will be taken at optimum shadow times (morning and evening) which are a function of the landing longitude. Proper picture taking times must therefore be programmed, dependent upon the planned landing longitude.

Another significant factor of the science data is the peak rate of accumulation. The highest peak rates are clearly in excess of the normal transmission capability, 300 or 600 bps in the clock track mode and 1200 bps in the autotrack mode. A single low resolution panoramic image, $2.16 \times 10^6 \text{ bits}$, is taken in a four minute interval, resulting in a 9 kbps data rate. The high resolution images are taken at a 12 kbps rate for 80 seconds. Consequently, the data must be buffered and stored to adjust to the transmission link rates. Figure 5.4-53 illustrates a typical data accumulation and transmission history.

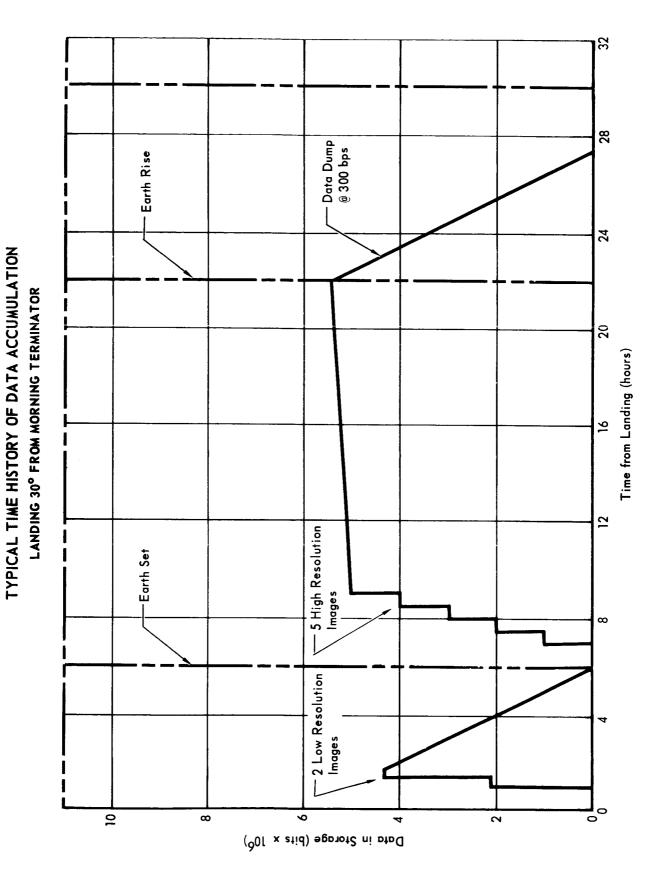


Figure 5.4-53 5.4-116

<u>Data Control Requirements</u> - The data control requirements fall into two interrelated groups. There is that group which is concerned with the instruments per se, and a group which is concerned with the recording and transmission of data.

The data control of the engineering measurements is straightforward as each instrumentation sensor output is always available for monitoring. Data control of the science measurements is more complex; first the instrument must be turned ON, second it must "prepare" a measurement, and finally at the appropriate time the measurement data must be collected. The measurement taking capability must be flexible in order to exploit the capability of the transmission systems. Experiment control is thus divided into two functions: (a) on/off and mode commands, and (b) subsequencing. Subsequencing concerns those commands that the experiment requires to perform the job, once the on and mode commands are given. Within a mission the instrument on/off controls must remain flexible. The internal instrument sequencing need not be alterable after launch.

The data handling subsystem must also control data recording and transmission rates. The data collection rates are defined from the experiment time line. From this time line the DHS must control the data storage subsystem recording rates. rate of data recording is necessary during the periods of visual imaging (9 or 12 kbps), while a low rate is necessary at other times (approximately 10 bps). transmission rates are established by the pointing accuracy of the high gain antenna. The information for rate control is outside the DHS sensing capabilities. However, since the DHS must control the transmission rate, this information must be fed into the system. Rate control data may be derived from either the command subsystem or the antenna Tracking Receiver At the minimum pointing accuracy, ten hours would be required to transmit all of the SL data, while only 2-1/2 hours would be required at the highest pointing accuracy. Figure 5.4-54 summarizes the data controls required. 5.4.9.3 Configuration Analysis - The large quantity of imaging data as well as the high data acquisition rates associated with this experiment dictate use of a tape recorder. The inherent nature of a tape recorder imposes a number of restrictions on the DHS interfaces and in some cases dictates a particular implementation. Readin data rates to the recorder must be relatively constant. That is, the recorder will not accept the bursts of data generated by most VOYAGER science experiments. This requirement for a constant tape recorder read-in rate leaves the telemetry/ data storage interface independent of this study. The questions that must be

DATA CONTROLS

SOURCE	MODES	INTERNAL SEQUENCE COMMANDS	OCCURRENCE RATE
Visual Imaging	2	12	2 pictures morning, 5 pictures afternoon
Atmospheric Properties	2	4	1/15 min, day/night; 1/1 min — sunrise/sunset
Alpha Spectrometer	2	4	3—8 hr counts, 1—2 hr count
Gas Chromatograph	3	1 .	8-20 min, 4-100 min and 2-50 min
Metabolism	2	4	1-5 hr in situ, 1-12 hr run
Growth	1	3	1-26 2/3 hr run
Subsurface Probe	3	3	Same as atmos prop plus gas sample collection
Spectroradiometer	2	2	1 continuous and 1—7 times per day
Soil Sample Acquisition	2	5 ·	1—2 hr operation and 4—40 min processes
Engineering Data	2	0	Continuous sensor operation, day and night mode

addressed is how to best control data flow to:(a) provide these uniform rates to the tape recorder and (b) minimize interruptions of the data transmission to Earth.

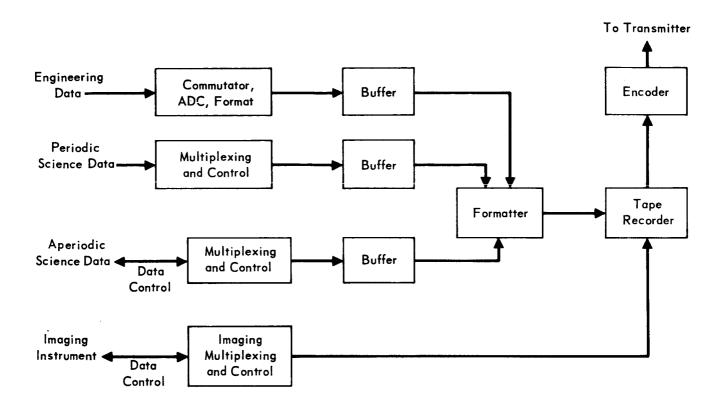
Functional Interface Definition - The basic function of any telemetry system is to format data into a coherent bit stream suitable for transmission. The VOYAGER Surface Laboratory will produce relatively little engineering data and large quantities of science data. The data must be interleaved such that none of the engineering data is lost in the interleaving process. Thus, whatever configuration is selected to perform the interleaving function, the telemetry subsystem must have knowledge when bursts of science data are to be generated. Given this information, the telemetry subsystem is also in a position to ensure that data buffers do not overflow with the resulting loss of information.

Specifically, if a data buffer is about to overflow and the tape recorder is in a dump sequence, the recorder can be stopped, the overflowing buffer read onto tape, and the tape dump sequence restarted. Finally, the DHS configuration was chosen to buffer non-imaging data during the night as well as during the tape recorder dump. The stored data can then be placed on tape at the end of the next picture taking interval. The data functional flow paths are illustrated in Figure 5.4-55.

The logical approach to giving telemetry a knowledge of when bursts of science data occur, and providing necessary control of data flow to and from storage, is to place control of these functions in the telemetry subsystem. At a minimum, the telemetry subsystem should provide on/off control of each science instrument and format the resulting data into storage. Since many instruments have multiple operational modes (each producing data in different quantities and formats), the telemetry subsystem would also logically control mode selection. Several science instruments require command signals in addition to simple on/off controls to sequence the instrument through a given experiment cycle. These commands (referred to here as subsequencing commands) could be generated by the telemetry subsystem via the science data subsystem or by the science data subsystem itself.

The choice here is deferred to a later portion of this study. In any case the gross on/off and mode selection control should be generated by the telemetry subsystem and routed to the science instruments via the science data subsystem. The telemetry should also control data flow within the DHS and perform formatting as data is placed in storage.

DATA FUNCTIONAL FLOW PATHS



DHS Implementation - The question of implementation is actually a problem of:

(a) how DHS programming is organized, (b) the degree of centralization of control functions, and (c) the programming technique used. Two programming techniques applicable to the VOYAGER SL are the hardwired concept and the stored program concept. The hardwired configuration, comparable to the Mariner Data Automation System, is attractive because of its simplicity, well understood techniques, and flight proven reliability. Experience has shown, however, that severe penalties must be paid for the inflexibility of the resulting system. There seems to be no way of preventing changes in experiment definition from propagating through to other portions of the DHS. The stored program concept (applied to telemetry) is relatively new and is presently being developed primarily for military space applications. Because of its recent development status, the stored program concept has not yet attained the full acceptance that hardwired systems have. Nevertheless, it is felt that the need for flexibility in experiment definition and the requirement for reprogrammable experiment sequencing necessitates stored program control.

The degree to which the controls are reprogrammable, however, is another question. In a totally centralized programmer, the reprogrammable memory would contain in core the entire formatting structure for both science and engineering data, the on/off controls (sequencing time line), and all subsequencing commands necessary to sequence each science instrument through its experiment program(s). The approach chosen for the SL DHS is to hardwire the data format tubes (see explanation of interlaced tube formatting technique in Section 5.4.11), and to store in core the switch addresses placed in the tube. This provides the flexibility of a stored program while permitting graceful degradation. In this system, failure of a core will cause loss of data from only its associated switch. If the formatting tubes were also stored, a single core failure could disrupt the entire telemetry formatting technique and cause catastrophic failure. Similarly, science instrument sequencing is partially stored program and partially hardwired. The sequencing time line (on/off and instrument mode selection) is stored in the telemetry core memory; the subsequencing commands however are, in general, hardwired and unique to a particular instrument.

The remaining question is how best to implement the science data subsystem data acquisition and instrument subsequencing. The approach chosen is a modularized technique whereby each science instrument has its own unique control unit.

The control units or SDS Remote Interface Units, as they have been designated, serve as interfacing devices between the SL telemetry subsystem and the science instruments. Each RIU is designed to operate a single experiment (gather data and generate subsequencing commands). It requires only on/off and a mode selection commands from the telemetry programmer; after receipt of such a command the RIU, without further assistance from telemetry, makes a complete measurement and transfers the resulting data to temporary storage in the telemetry subsystem. permits modification of experiments with changes isolated to the RIU. Science sequencing (time line) can be modified by changing the stored program. A summary of the configuration analysis is presented in Figure 5.4-56. 5.4.9.4 Conclusions - Versatile telemetry and science data subsystems are required for the SL data acquisition function. The functional interface between these subsystems consists of TM on/off control and detailed SDS experiment control. A decentralized SDS, composed of RIU's for each experiment presents the best compromise between performing all of the sequencing in either the TM or the SDS. This concept limits the propagation of a change to a single RIU in the SDS and/or instructions stored in an electrically alterable program in the TM. Executive control of science measurements has been assigned to the telemetry programmer, which also controls the gross data output format. The telemetry subsystem also contains the data buffer and controls the flow of data both to and from the data storage tape recorder.

TELEMETRY PROGRAMMER CONFIGURATION ANALYSIS SUMMARY

DESIGN APPROACH	ADVANTAGES	DISADVANT AGES
Hardwired	 Flight proven Reliable Standard design 	 Inflexible in operation Changes propagate thru system
Hardwired instructions with core storage for addresses and controls	 Reliable operation Gate addresses and sequence instructions readily alterable Early design freeze Changes limited to RIU or stored program 	 Requires reliable low temperature memory read/write Slightly more power consumption than hardwired system
Stored program instructions and addresses	 Maximum flexibility Changes limited to RIU or stored program 	 Contains single point failure modes Sensitive to shutdown transients Requires software development Most sensitive to temperature environment

5.4.10 Storage Device Selection - In the Surface Laboratory (SL), storage devices are required for the multiplexer programmer, nighttime data acquisition, image data acquisition, and buffering. A study was made of the devices available now and in the near future. Selection was based on the best possible match between storage devices and the requirements of each individual application, resulting in the following:

Application

Storage Device

Multiplexer programmer

Core memory

Nighttime data acquisition

Tape storage

Image data acquisition

Tape storage

Buffering

Core memory

5.4.10.1 <u>Requirements</u> - Functional requirements vary with the application and can be summarized as follows:

Stored Program Memory

Capacity: 40,000 to 60,000 bits.

Cycle time: 2 to 10 msec.

Random access.

Word size: multiple of 8 bits.

Non-volatile storage.

Non-destructive readout (overall system).

Electrically alterable.

Nighttime Data Storage

Capacity: 250,000 to 500,000 bits.

Serial input: \geq 10 bps (variable).

Serial output: < 1200 bps (variable).

Mass Storage

Capacity: 10⁶ to 10⁸ bits.

Readout rate: 1200 bps, 200 bps.

Read in rate: 5,000 to 10,000 bps.

Buffers

Capacity: 100 bits to 10,000 bits.

Input rate: < 3300 bps.

Output rate: < 1200 bps.

All devices must meet the environmental requirements including sterilization temperatures and radiation. They must be highly reliable to prevent compromise of the SL mission success. In addition, weight, volume and power must be minimized.

5.4.10.2 <u>Design Approaches</u> - The devices considered for the SL telecommunications applications were: semiconductor memories, static magnetic memories, and dynamic magnetic memories. Read - only memories (e.g., transformer or capacitor memories) were not considered since all applications require electrically alterable storage.

5.4.10.2.1 <u>Semiconductor Memories</u> - Two types of semiconductor memories were considered: bipolar translator and MOSFET arrays. The major disadvantage of these memories is their volatility. However, for small scratchpad memories they may be acceptable.

Individual arrays of monolithic bipolar flip-flops are presently available in 9-bit and 16-bit capacities. With addressing electronics, the power requirement is about 20 mW per bit. A small array of this type, has been reported. It has a capacity of four 49-bit words on a single monolithic chip, 60 x 80 mils in size, placed in a 16 lead package. These units have been interconnected into larger arrays providing a complete memory having a 256 word, 72 bit capacity with a 150 nanosecond write cycle time.

In the MOSFET memory, field effect transistors are connected either as flip-flop elements or as charge storage elements. In either case the circuit impedances are high, resulting in lower power requirements and a slower operating speed than for the bipolar arrays. At the present time 100-bit shift registers are available on a single chip, with the promise of larger arrays to follow. The holding power of MOSFET arrays is very small. Present power requirements are 100 microwatts per bit for the memory cell and 200 microwatts per bit for the complete memory.

5.4.10.2.2 <u>Static Magnetic Memories</u> - The static magnetic memories studied were: magnetic core, plated wire and etched permalloy. Multi-aperture devices were not included because of their greater size and write-power requirements, and lack of significant advantage over cores for the SL application.

Magnetic Core - Magnetic core memories consist of individual discrete toroidal magnetic cores strung on conductive wires to form planar arrays, storing a single bit of information per core. There are three major core memory organization arrangements, referred to as 2D, 3D, and 2-1/2D. The 2D memory is characterized by the simplest conductor threading pattern. Its advantage is comparatively

high operational speed. The 3D memory is characterized by a larger number of conductors threading each core; but the core selection electronics is reduced over that required for 2D at the price of slower operating speed. The 2-1/2D organization attempts to combine the best features of both the 2D and 3D memories, i.e., minimize core selection electronics while maintaining high operating speeds.

The efficiency of the 2D organization is low for small words (less than 100 bits). For small words, and memories of less than 8,000 words, the 3D organization is most efficient. For larger memories, 2-1/2D organizations hold the advantage.

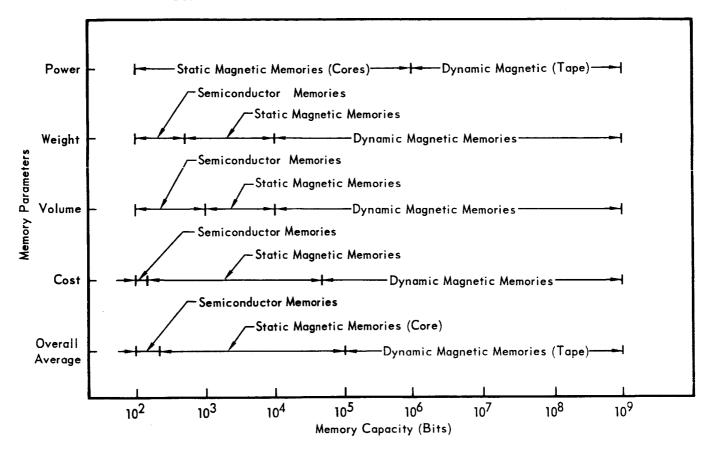
Some of the outstanding characteristics of the magnetic core memory are as follows:

- o Packing density is approximately 500 bits per cubic inch for memories (including electronics) up to 10^5 bit capacity. The density increases to 5,000 bits per cubic inch for larger memories. The present limit is 10^7 bits.
- o Memory organization provides for random access and is thus suitable for serially acquired data.
- o Readout is non-destructive (with normal re-write cycle) and data is maintained in the event of power failure.
- o Cycle times range from 600 nanoseconds to 10 microseconds.

Plated Wire - A more recent development than the magnetic core memory is the plated wire memory. The basic memory element consists of a segment of plated magnetic material surrounding a conductive wire. A continuous wire plating process results in a continuum of these memory elements along the length of the wire. The plated wire memory plane is similar to a 2D or word organized memory utilizing magnetic cores. However, it differs in that the plate itself may provide either Destructive Readout (DRO) or Non-Destructive Readout (NDRO) depending on the amplitude of the drive current during reading. The plated wire memory falls in the category of thin film memory systems, and represents the most practical form of thin-film memory to date.

There is some evidence to indicate that, in the NDRO mode of operation, data will eventually be lost due to the effects of the magnetic film. This has been observed after approximately 10^6 readout cycles of a previously stored data word. However, this problem is not encountered in the DRO mode because of the normal re-write cycle. An additional disadvantage in the use of plated wire memories for a spacecraft is that memory planes are sensitive to shock and vibration. Therefore, plated wire memories are not attractive for the SL application.

COMPARISON CHART FOR DATA STORAGE SYSTEMS



Etched Permalloy - The etched permalloy memory is another recent approach to the batch fabrication of large capacity, low cost memories. This type of memory is noteworthy because of its low power requirements, low weight, and small size. Although not as fast in operation as either ferrite core or plated wire memories, the etched permalloy memory becomes most attractive in the range of 10^6 bits and higher.

5.4.10.2.3 <u>Dynamic Magnetic Memories</u> - A tape recorder is the only dynamic magnetic memory considered for the SL application. There are three types of tape recorders to be considered: coplanar reel-to-reel, coaxial reel-to-reel and endless loop. The endless loop configuration is limited in capacity and information rate, which disqualifies it from consideration for the SL.

The two reel-to-reel configurations are quite similar in performance and both can meet the SL mass storage requirements. The choice of configuration should then be based on the allowable volume and form factor.

5.4.10.3 <u>Configuration Comparison</u> - Figure 5.4-57 illustrates the range of application of various types of memories for various memory parameters, as a function of memory capacity. The four parameters, power, weight, volume and cost have been plotted. In addition, an "overall average" has been estimated based on the application ranges for the power, weight, volume and cost. Addition of other criteria or constraints such as a requirement for a non-volatile storage, or random access, might shift the range or eliminate a configuration. However, the "overall average" is a good measure of memory applicability.

The "overall average" indicates that in the range below 200 bits, semiconductor memories are preferred. In the range from 200 to 10^5 bits, the magnetic core approach is most advantageous, and in the range from 10^5 to 10^9 bits, magnetic tape is the best approach. In the large capacity category, etched permalloy cannot compete with magnetic tapes because of size and weight.

5.4.10.4 <u>Recommended Design Approaches</u> - The criteria for selection of the memory technique for the various applications are (in order of importance): meets functional requirements, reliability, power, weight, volume, environmental characteristics, and cost.

Stored Program Memory - The required bit capacity of 40k to 60k bits for the Stored Program Memory falls sufficiently below the 10^5 bit crossover point on the Comparison Chart to clearly favor the use of core memory. Also, the requirement

for random access precludes the use of a tape memory. The very small cycle time of 10 msec and the 8-bit word results in a power consumption for core memory considerably less than one watt. The additional requirements of non-volatility of storage and non-destructive readout are also met by the core memory.

Electronic Memories, Inc., under JPL direction; has recently made a study of the effect of sterilization, at both 135°C temperature and ETO, on core memory components. All memory components survived both types of sterilization. Although the complete memory system was not tested, the survival of the components indicates that the core memory is sterilizable by either method.

Nighttime Data - The requirement of 250k to 500k bit capacity argues for tape memory. Since there is no requirement for random access, the tape choice is sufficient. The very low input bit rate of 10 bps allows the recorder to be stopped and started to accommodate intermittently available data. The limit ratio between playback and record rates is 120:1, which may necessitate the use of separate record and playback heads, a normally available optional feature.

Several tape recorder manufacturers have given assurances that tape recorder mechanisms and drives which will survive the sterilization temperature are available. Also, Memorex has developed, under a NASA - Goddard contract, a Kapton magnetic tape which will survive 145°C non-operating and operate at 150°F. This tape is now in pilot production.

<u>Mass Storage</u> - A large bit capacity in the range of 10^6 to 10^8 bits definitely requires tape storage. The low record and playback rates of up to 1200 bps can be accommodated on a single track.

<u>Buffers</u> - The only candidates suitable for buffers are semiconductor memories and core memories. Even at the low storage requirement of 100 bits the power requirement makes semiconductor memories only marginally suitable, and power consumption would become prohibitive at 10^4 bits. The two candidates are comparable in terms of weight and volume. There is a clear cut choice in favor of core memory in the cost category. The final choice is thus core memory.

5.4.11 Multiplexing Techniques - This section presents a summary of alternate multiplexing techniques considered for use in the SL Telemetry Subsystem. As used in this section, the term multiplexing includes the functional operations of gating. decoding and channel sequencing (programming). Due to the dependence of the Data Handling System (DHS) configurations (see section 5.4.9) upon the multiplexing technique employed, multiplexing trade studies were performed for each DHS configuration under consideration (hardwired, hybrid and multiprocessor). Since the DHS configuration trade study resulted in the selection of the hybrid configuration for the baseline system, the multiplexer trade studies for the hardwired and multiprocessor configurations are only summarized briefly, with the major emphasis placed on the hybrid configuration. Reference 5.4-21 requested that absolute rate commutation be considered. Two methods of absolute rate commutation, the burst and strobe methods, were considered. The burst method requires a buffer and is compatible only with the burst tube method of programming and a storedprogram multiplexer. The strobe method has the disadvantage of great programming difficulty with resultant lack of flexibility. Therefore these absolute rate commutation methods were not included in the multiplexer trade studies. 5.4.11.1 Multiplexing Trade Study for Hardwired DHS - Three multiplexing techniques were evaluated for the hardwired DHS configuration: ring counter, matrix programming and interlaced tube. The ring counter and matrix programming techniques have been used in past and present systems. The interlaced tube programming method, a relatively new technique, is described in Section 5.4.11.3.

Criteria used for hardwired DHS multiplexer trade-offs were reliability, physical parameters (size, weight, power, etc.), performance and flexibility, in order of decreasing importance. The trade-off study indicated that the matrix programmer was best in all categories except performance, where the interlaced tube method provides a somewhat better sample efficiency. The ring counter method was found to rank lowest in all categories.

As a result of this trade study the matrix programmer was selected to represent the hardwired system in the DHS configuration trade study.

5.4.11.2 <u>Multiplexing Trade Study for Multiprocessor DHS</u> - The programming techniques evaluated in the multiplexer trade-off for the multiprocessor DHS configuration were multi-access, threaded-list, interlaced tube and burst tube programming in conjunction with delta-tree encoder, analog pulse-width conversion and random select gate sampling methods. The random select gate was found to be the best sampling method for all of the programming techniques studied.

Since physical, reliability and performance factors are insensitive to the programming technique used with the multiprocessor, the criteria used for trade-off were sample efficiency, average processor instruction rate and storage requirements, in order of decreasing importance. The results of the study indicated that the interlaced tube requires the least amount of storage and the lowest instruction execution rate, while running a close second to the burst tube method in sample efficiency. Therefore, the interlaced tube technique would represent a multiprocessor DHS configuration.

5.4.11.3 <u>Multiplexing Trade Study for Hybrid DHS</u> - In the hybrid DHS configuration the multiplexer programmer is a stored program sequencing unit. As a result of an optimization study (Reference 5.4-22) random-select FET analog gates were selected for use with the stored-program sequencing. Therefore, the difference between the techniques discussed below is confined to core storage and channel address logic. The three programming techniques evaluated for the hybrid DHS configuration are multiple access, table look-up and interlaced tube.

Multiple-Access Program - The multiple-access programming technique has been used predominately in stored-program decommutator stations and recently has been adopted for the Titan III and Poseidon PCM telemetry systems. This technique is easily implemented and efficient in core utilization. The multiple-access terminology is derived from the need to access memory two or more times for all subcommutation frames (i.e., first-level subframes require two memory accesses; second-level sub-subframes require three memory accesses, etc.).

One additional flag bit per memory word is required to indicate when the content represents a subframe memory location rather than a channel address. A special memory-position index number is used at the end of each frame to reset the subframe instruction in the appropriate higher-level frame. Some scratchpad is required for storage of the pointers for each rate group. Core memory programming is easily accomplished by listing channel addresses and index number in order of sequence and sampling frequency.

Look-Up Table Program - The look-up table program technique is the simplest form of stored-program sequencing in terms of logic operations but requires large memory capacity. Programming is achieved simply by listing all channel addresses in order of major frame sequencing, repeating channel numbers as required until the major frame is complete.

Storage capacity is determined by the length of the major frame which is the product of the maximum frame lengths within each commutation level, assuming that

all frames within a given subcommutation level are even multiples of the longest frame within that level. If this condition is not met, it will be necessary to take the product of all frame lengths within the multiplexing pattern. Under such conditions, the major frame length can exceed the time duration of the lowest rate subframe. In any case, memory required to satisfy the SLS multiplexing is extremely large using this technique.

Interlaced Tube Program - The interlaced tube programming technique is similar to the multiple-access programming technique described above since it also requires scratchpad and special index instructions. Figure 5.4-58 is an illustrative example of an arbitrary multiplexing format produced by the interlaced tube. The constuction simplicity of these formats is clearly evident. For purposes of this description, a major frame represents the total number of samples required to sequence through all data sources and a minor frame is the least number of samples required before a data source is repeated (determined by the highest sampling frequency within the data ensemble).

The interlaced-tube format is constructed by first listing all measurements in groups (tubes) of descending sampling frequency, as shown. The number of major frame samples, $S_{\rm mf}$, is determined by:

$$S_{mf} = \sum_{r_{min}}^{r_{max}} N_r \left(\frac{r}{r_{min}}\right)$$

where r = sampling rate of a given rate group

 N_r = number of samples in the r^{th} rate group

 r_{min} = lowest sampling frequency

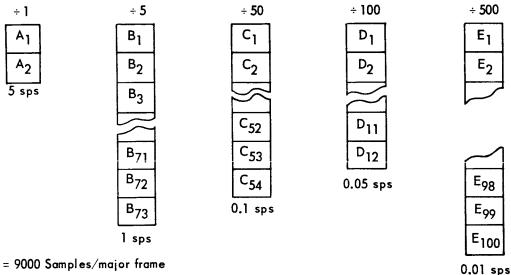
 r_{max} = highest sampling frequency

The number of prime frame samples, S_{pf} , is:

$$S_{pf} = S_{mf} \left(\frac{r_{min}}{r_{max}} \right)$$

The system sample rate in sps is, of course, S_{pf} (r_{max}). If the minor frame is not an integer number of samples, spare channels must be added in any desired combination to meet this requirement. Although this constraint is similar to other multiplexing techniques, it should be noted that the interlaced-tube procedure generally requires fewer spares, resulting in greater sampling efficiency. Under no condition will it result in an efficiency lower than the other techniques considered.

INTERLACED TUBE FORMAT EXAMPLE



 $S_{mf} = 9000 Samples/major frame$

$$S_{pf} = \frac{S_{mf}}{500} = 18 \text{ Samples/minor frame}$$

Sample Rate = $18 \times 5 = 90 \text{ sps}$

A₁, A₂, B₁, B₂, B₃, B₄, B₅, B₆, B₇, B₈, B₉, B₁₀, B₁₁, B₁₂, B₁₃, B₁₄, B₁₅, B₁₆ Frame No. 1

Frame No. 2 A₁, A₂, B₁₇, B₁₈, B₁₉, B₂₀, B₂₁, B₂₂, B₂₃, B₂₄, B₂₅, B₂₆, B₂₇, B₂₈, B₂₉, B₃₀, B₃₁, B₃₂

Frame No. 5 A₁, A₂, B₆₅, B₆₆, B₆₇, B₆₈, B₆₉, B₇₀, B₇₁, B₇₂, B₇₃, C₁, C₂, C₃, C₄, C₅, C₆, C₇

A₁, A₂, B₁, B₂, B₃, B₄, B₅, B₆, B₇, B₈, B₉, B₁₀, B₁₁, B₁₂, B₁₃, B₁₄, B₁₅, B₁₆ Frame No. 6

A₁, A₂, B₆₅, B₆₆, B₆₇, B₆₈, B₆₉, B₇₀, B₇₁, B₇₂, B₇₃, E₉₄, E₉₅, E₉₆, E₉₇, E₉₈, E₉₉, E₁₀₀ Frame No. 500

The channel sequence format produced by the tube method shown is generated as follows:

During the first minor frame, the two 5-sps plus the first sixteen 1-sps channels are sampled. During the second minor frame, the two 5-sps plus pins 17 through 32 of the 1-sps channels are sampled. During the fifth minor frame, the two 5-sps and last nine pins of the 1-sps plus the first seven pins of the 0.1-sps channels are sampled. The next five minor frames will be identical to the above sequence except that pins 8 through 14 of the 0.1-sps tube will be sampled during the tenth frame. This procedure continues until the five-hundredth minor frame; at this time the last seven pins of the 0.01-sps tube are finally sampled. The sequence then repeats.

Hybrid Stored-Program Trade-Off - The results of the hybrid system trade-off study are presented in Figure 5.4-59. The criteria used in the evaluation are physical parameters, reliability, flexibility and performance. Reliability is weighted the heaviest, followed by physical parameters (power and weight), performance and flexibility in that order. The weighting factors used were 0.4, 0.3, 0.2 and 0.1 respectively.

Due to inefficient memory utilization, the look-up table programming technique suffers in physical and reliability grading. Although the identical logic algorithm can be used for both interlaced-tube and multiple-access techniques, multiple-access does require a few more words in storage (this difference is too small to be observed in the grading numbers).

Because all addresses associated with the higher sampling rate groups are repeated many times in the look-up table memory, programming of software changes becomes considerably more difficult than with the other techniques. Programming for the multiple-access techniques is slightly more complicated because of the extra jump instructions required and can become considerably more complicated if super-commutation (cross strapping) is required. Performance is confined to the improved sampling efficiency of the interlaced tube. Look-up table is given a higher ranking than multiple-access since it is possible to program the look-up table with a tube format; however, programming would be further complicated.

Interlaced-tube programming is selected for the hybrid DHS configuration since it is ranked highest under all criteria.

5.4.11.4 <u>Reliability Considerations</u> - Detailed reliability analysis of a commutator design concept was conducted and methods determined by which the reliability can be

TRADE STUDY SUMMARY, HYBRID MULTIPLEXING

	MATRIX 0	MATRIX OF DESIGN APPROACHES	CHES	
CRITERIA	NO. 1 LOOK-UP TABLE	NO. 2 INTERLACED TUBE	NO. 2 NO. 3 INTERLACED TUBE MULTIPLE ACCESS	SELECTION 2
Physical Weight — 0.3	Power, 11.5 watts Weight, 10 lb	Power, 2.4 watts Weight, 1.5 lb	Power, 2.4 watts Weight, 1.5 lb	2-3-1
Reliability Weight — 0.4	.27 MTBF 19 × 10 ³	.4 MTBF 28 × 10 ³	MTBF 28 x 10 ³	2-3-1
Flexibility Weight — 0.1	Maximum number of .02 software modification to accommodate single measurement change.	Simplest to change	.1 Easy to change09 More difficult e programming re- quired if cross strapping is used.	2-3-1
Performance Weight – 0.2	Low sample effications of the ciency unless tube format used.	Good sample efficiency.	Low sample efficiency.	2-1-3
Total Grading	0.49	1.0	0.89	

maximized. The methods essentially consist of incorporation of a combination of multi-channel cooperative and circuit block redundancies.

The basis for the analysis was <u>elimination</u> of critical single point failures, <u>improvement</u> of fail-safe design features, and <u>maximization</u> of total and partial probability of successful commutator operation.

A generic PCM commutator and encoder design, shown in Figure 5.4-60, contains the basic elements for operation and handling of High Level (HL), Low Level (LL), BiLevel (BL) and Digital (D) groups of input data signals. The generic design assumes a standard time division multiplexing method of sampling and gathering input data signals for presentation to a transmitter modulator. All data switches were assumed to be Junction Field Effect Transistors (JFET). Similar analysis utilizing Metal Oxide Silicon Field Effect Transistors (MOSFET) could be conducted.

In the analysis, the 120 HL analog data channel group was analyzed and designed as shown in Figure 5.4-61. The reliability of this design was estimated for retrieval of total data, a subgroup (deck) of data and for an individual data channel. A detailed reliability analysis of the generic design was conducted to optimize the design reliability, as shown in Figure 5.4-62. This figure shows the optimum arrangement of data channels which inherently contains multi-channel cooperative redundancy and maximized probability of partial data retrieval. The analysis was conducted as follows:

The basic JFET data switch was assigned a failure rate (f). All other elements were assigned an effective failure rate expressed as some multiple of (f) for purely comparative purposes. Different data channel arrangements were analyzed and the comparative reliability was estimated for each arrangement. Results are shown in Figure 5.4-63.

Limited circuit block redundancy, as shown in Figure 5.4-64, was added in the most critical switching decks, namely decks F5, T5, and S5, in that order. This addition optimizes total data retrieval probability at minimum expense of part increases.

Summary - The reliability of a PCM Commutator data channel group has been optimally maximized by incorporation of multi-channel-cooperative and limited block redundancy and is the recommended design approach for the Telemetry Commutator. The multi-channel-cooperative redundancy feature essentially decentralizes the first level of analog data switches for optimum reliability and data switch independence in event of any switch failure. Further decentralization from that shown in Figure 5.4-62 however reduces probability of partial and total data channel

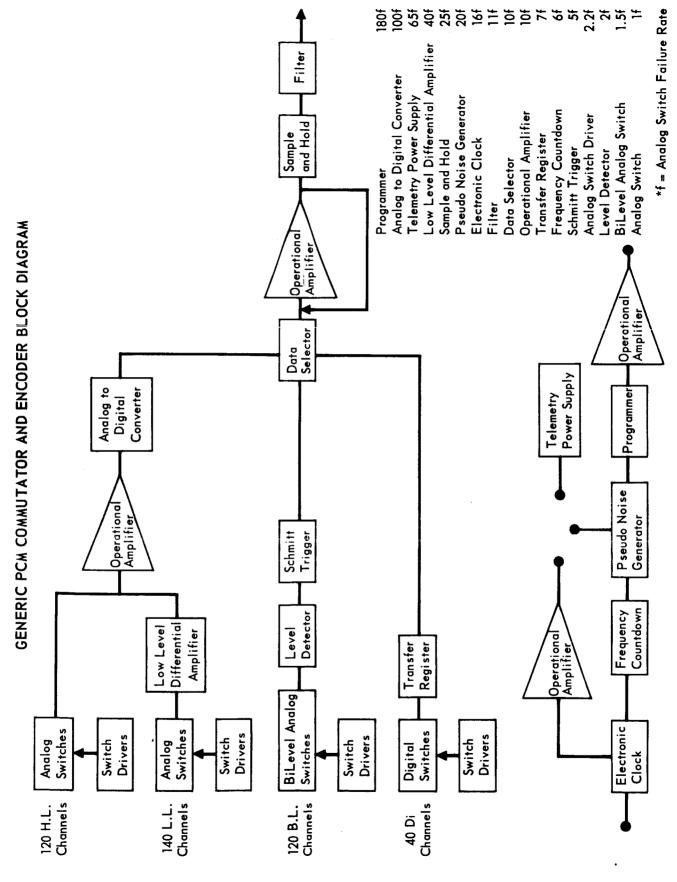
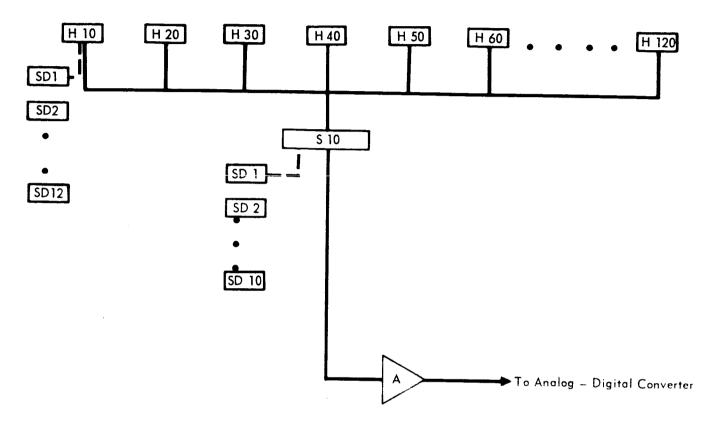


Figure 5.4-60

HIGH LEVEL ANALOG SIGNAL GROUP



Notes:

- 1. H10 First Level Switch Deck (Subgroup) containing 10 Analog Switches.
- 2. S10 Second Level Switch Deck containing 10 Analog Switches.
- 3. SD1 (Switch Driver) Drives all switches in Subgroup H10.
- 4. Another SD1 drives the first position switch in Deck S10.

H 24 H 20 SD 1 H 19 OPTIMIZED CHANNEL ARRANGEMENT (120 CHANNEL SPLIT INTO 4 INDEPENDENT GROUPINGS, 5 CHANNELS SUBGROUP) SD 24 SD 20 1 18 SD 1 H 14 SD 1 H 13 SD 18 SD 14 H 12 SD 2 SD 1 ω Ι SD 1 I SD 12 SD 7 SD 8 <u> 1 OS</u> 9 H Н 2 i as SD 2 9 QS

Figure 5.4-62 5.4-139

HIGH LEVEL ANALOG DATA GROUP RELIABILITY SUMMARY

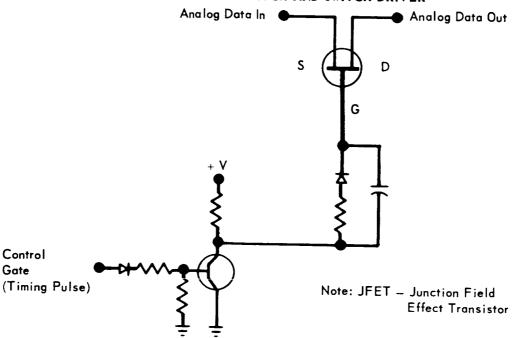
GROUP	SUBGROUP	CHANNEL	REMARKS
235f	204f	78f	
248f	201f	91f	
245f	221f	82f	
238f	201f	82f	·
237f	210f	78f	
264f	148f	68f	First level data group divided into
			independent halves
315f	107f/5 Channels	60f	First level data group divided
	214f/10 Channels		into independent fourths
271f	65f/5 Channels	34f	Redundant F5 and T5 analog switches
	130f/10 Channels		switch drivers and programmer sequencers
< 235f	< 65f/5 Channels	<34f	Redundant S5 analog switches,
	< 130f/10 Channels		switch drivers, and programmer
		!	sequencers
	235f 248f 245f 238f 237f 264f 315f 271f	235f 204f 248f 201f 245f 221f 238f 201f 237f 210f 264f 148f 315f 107f/5 Channels 214f/10 Channels 271f 65f/5 Channels 130f/10 Channels < 235f < 65f/5 Channels	235f 204f 78f 248f 201f 91f 245f 221f 82f 238f 201f 82f 237f 210f 78f 264f 148f 68f 315f 107f/5 Channels 60f 214f/10 Channels 271f 65f/5 Channels 34f 130f/10 Channels < 34f

NOTE: 1. (f) Values for the last three design configurations are cumulative and represent the optimum design approach.

- 2. As the (f) values are decreased, the reliability is increased exponentially.
- 3. If is equivalent to an analog switch failure rate.

COMPARISON OF BASIC AND REDUNDANT CIRCUITRY

(a) JFET ANALOG SWITCH AND SWITCH DRIVER



(b) REDUNDANT JEET ANALOG SWITCHES AND REDUNDANT SWITCH DRIVERS

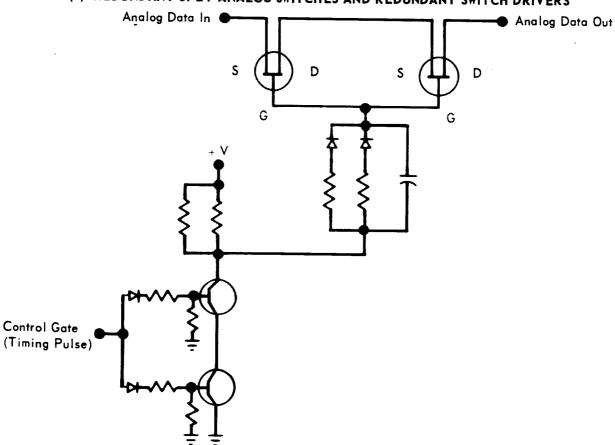


Figure 5.4-64

retrieval for the 120 data channels considered.

5.4.12 <u>Instrumentation</u> - The term "Instrumentation Equipment" is used to designate the engineering measurement portion of the telemetry system where the engineering data signals are sensed and conditioned to outputs compatible with the PCM encoders. This equipment consists of transducers, signal conditioners, and associated power supplies.

5.4.12.1 <u>Transducers</u> - The major portion of the SLS engineering measurements requiring transducers can be classified in three categories; temperature, pressure and motion.

Temperature Measurements - Preliminary requirements for 37 SL and associated subsystem temperature measurements have been established per the SLS Instrumentation List. The temperature ranges are from a low of -200°F to a high of 200°F in five overlapping spans. The specific temperature measurement requirements are shown below.

SLS Temperature Measurement Requirements

Temp Range	<u>Span</u>	No. 1	Measurements
0 to 120°F	120°F		4
25 to 150°F	125°F		6
-10 to 150°F	160°F		1
-50 to 200°F	250°F		8
-200 to 150°F	350°F		18
		Total	37

All the temperature monitoring points are located on equipment, components, or structures. Surface type temperature sensors that can be attached to variety of surface contours and shapes are therefore required. Thermistors, platinum resistance sensors, and thermocouples are likely candidates. Platinum resistance sensors in a conventional wheatstone bridge arrangement are preferred for the temperature measurements in these ranges, for the following reasons:

- O Superior R-T characteristics for wide temperature span. Typical span is -326°F to 1000°F.
- $^{\circ}$ Excellent stability of calibration. The interpolation instrument that is used from -182.97°C to 630.5°C on the International Temperature Scale is the platinum resistance thermometer.
- O Higher output voltage than thermocouples.
- O Control of output voltage/degree exactly as desired over wide temperature limits by adjustment of excitation current or by bridge design

- O Reference junctions not required
- O Ease of calibration (only small number of calibration points are required).

Alternate bridge designs were also investigated. There were the full bridge, half bridge and the Mariner C single ended configurations. The full bridge and half bridge are shown in Figure 5.4-65. The full bridge method is the preferred approach, because the common mode noise signals picked up by the lead wires are rejected by the differential amplifier in the low level commutator and lead wire voltage drop errors are minimized. Computer calculations for bridge designs for typical SLS temperature ranges were contributed by Rosemount Engineering Company and appear in Figure 5.4-66. The main considerations in the design are minimum power consumption and linear 0-40mV output using a sensing element R_O value as high as practical without introducing self-heating error. Power consumption is under 2 mW for the ranges shown. Using wire-wound, 5 ppm/°C bridge completion resistors, the temperature coefficient effects were calculated and found to be negligible.

<u>Pressure Measurements</u> - Eight pressure measurements are presently required to monitor the SLS thermal control equipment pressures. The pressure range required is 0 to 15 psia. Six types of pressure transducers were considered as being potentially capable of meeting the VOYAGER requirements. The types are potentiometric, bonded gage, unbonded strain gage, variable reluctance, capacitive or LVTD type. Of these, the potentiometric type is preferred for the following reasons.

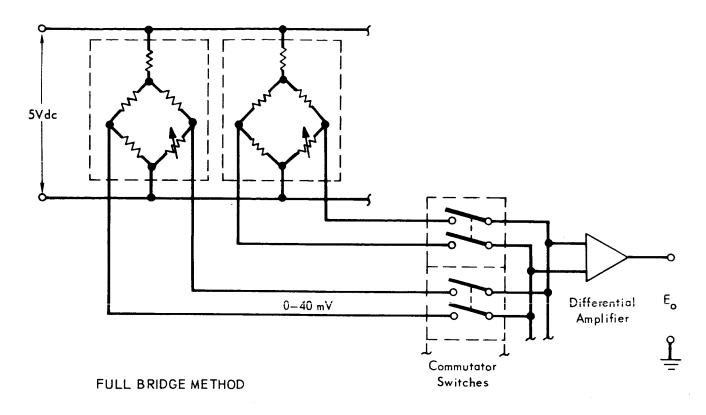
- O Lowest power consumption for 5V output (.25 mW)
- No amplifier required.
- Relatively low cost.
- O Simplicity and reliability.
- O Lowest weight.

5.4.12.2 <u>Signal Conditioners</u> - The more complex SLS signal conditioning required includes dc current monitoring and pyrotechnic current pulse detection.

<u>Current Monitoring</u> - Eight dc current measurements are presently required in the SLS power subsystem. The ranges are 0-2A and 0-5A.

The two methods considered for monitoring dc current were, calibrated shunts with amplification by the telemetry low level dc amplifier, and an individual magnetic amplifier for each measurement. The shunt method results in a savings in weight and overall power consumption. The disadvantage of this method is that accuracies are poor near the zero point. To a lesser degree, this is also true of the magnetic amplifiers. Shunt monitoring is capable of meeting the accuracy

TEMPERATURE MEASUREMENT METHODS



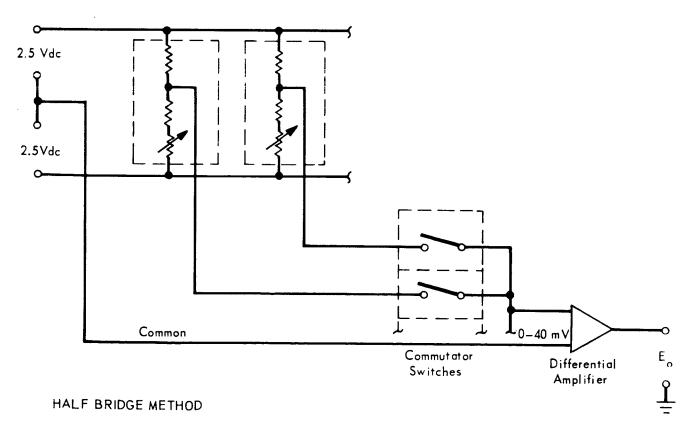
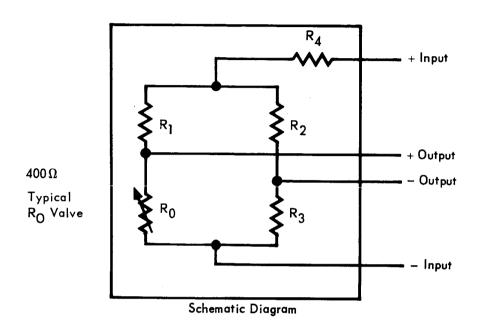


Figure 5.4-65

5.4-144

TEMPERATURE SENSOR CALCULATIONS



TEMPERATURE	BRIDG	E RESISTAN	ICE VALU	IES IN OHMS	POWER	TEMPERATURE COEFFICIENT
RANGES (°F)	R ₃	R ₂	R ₄	R ₁	REQ.	EFFECTS
-200° to +150°	200	8,380	15,000	7,956	1.3 mW	4.62 x 10 ⁻⁷ volts
- 50° to +200°	300	9,361	7,500	10,201	1.99 mW	6.08 x 10 ⁻⁷ volts

Input Required: 5 volts
Output: 0-40 mV

requirements and will be used for the battery load current measurements. Magnetic amplifier type circuits will be used for battery charge current measurements, where greater accuracy and circuit isolation are needed. The weight and power savings of using shunts as compared to individual magnetic amplifiers are approximately 1.5 lbs. and 2 watts.

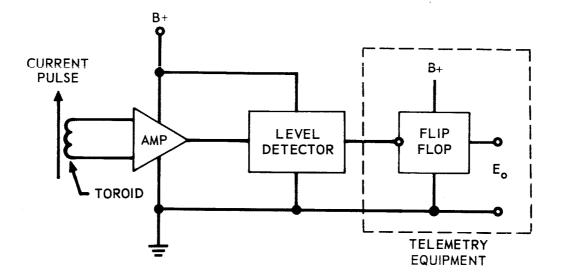
Pyrotechnic Current Pulse Detector - The detection of a firing current pulse is required for each of 20 squib cartridges in the pyrotechnic subsystem. Safety considerations prevent a hardwire connection to the pyrotechnic firing circuits. The current pulse can be monitored by a current transformer with a hole through which the return leg of the squib wire may pass. Detecting a current pulse is a less complex problem than monitoring current, since the current pulse is dynamic in nature. This eliminates the need for magnetic amplifiers and other associated circuitry necessary for dc monitoring. Figure 5.4-67 is a block diagram of a current pulse detector. The pulse transformer is fabricated in the form of toroid in such a manner that a single turn of the pyrotechnic lead wire is sufficient for pulse detection. The amplifier magnifies the pulse and provides a impedance match between the transformer and the level detector. The level detector is adjusted so that spike amplitude and spike energy are combined to give the necessary signal required to make the telemetry flip-flop change states. The flip-flop retains this information until sampled by the commutator.

5.4.13 Aliasing Data Compression - The SLS baseline telemetry subsystem does not include data compression. However, we have studied its feasibility to enhance subsystem performance by providing higher tolerance to the effects of uncertain environmental factors, and it seems an attractive alternative. System design and operation can be described as follows:

A typical instrumentation list defines the sample rate requirements, based on expected vehicle performance in an assumed environment. If these sample rate requirements are underestimated, significant measurement errors may be introduced; on the other hand, if the sample rate requirements are adequate, sampling at higher rates would result in unnecessary data transmission.

In the SL data system multiplexer sampling rates would be increased to about ten times the required rate. The data compressor separates those samples which would have been provided by a lower-speed multiplexer, and sends them on without modification. An appropriate compression algorithm (probably First-Order Interpolation) is applied to the remaining samples. If the original sample rate requirements are adequate, the compressor produces no additional data. If any requirements

PYROTECHNIC CURRENT PULSE DETECTOR



are inadequate, the compressor stores additional samples of excessively active channels for subsequent transmission.

By increasing the communication link capability about 10%, the data compressor output frame format would include all required data samples, followed by an additional 10% of compressed data samples. For example, if the required sample rate were 100 sps, the compressor output would be 110 sps (the first 100 time slots being the required samples and the last 10 containing any excess samples produced by the compression algorithm). Thus, if the highest per-channel sample rate required were 1 sps, at least ten channels could be adaptively increased to 2 sps; similarly one channel could be sampled at 10 sps. If the duration of the excessive activity is limited, or if the channel activity is not too excessive, even greater adaptivity can be expected.

Reliability - The calculated data compressor failure rate is about 2.81% per 1000 hours, based on the parts count for existing ground data compressors capable of performing similar operations. Obviously, this reliability figure can vary as a function of the compressed data store (buffer) capacity but it is not likely to become a poor risk item. If the multiplexer is designed to operate at both the required sample rates and an order of magnitude faster, the data compressor could be bypassed by ground command any time prior to FC separation.

<u>Conclusions</u> - Aliasing data compression is attractive for the SL TM system because it provides a tolerance to the environmental unpredictability and since the data compressor power consumption (due primarily to core memory storage) is quite low. It is not included in the baseline because the compressions have not been verified by simulation <u>and</u> because a specific hardware implementation has not been formulated. We feel that once these steps are completed, aliasing compression will be a high-value candidate for inclusion in the TM system.

REFERENCES

- 5.4-1 Mars Mission Communication Analysis, Philco-Ford Corporation, TR2531.
- 5.4-2 Boeing/Philco Final Technical Report, "VOYAGER Spacecraft System, Volume A, Preferred Design for Flight Spacecraft and Hardware Subsystems, Part II, Report No. D2-82709-1," The Boeing Company, July 1965 (VOYAGER study performed for JPL).
- 5.4-3 I. M. Jacobs, "Sequential Decoding for Efficient Communication from Deep Space," UCSD 1932, September 30, 1966.
- 5.4-4 G.D.Forney, Jr., "Concatenated Codes," MIT Res. Lab. of Elec., TR-440, December 1, 1965.
- 5.4-5 Dozencroft, J. M. and Jacobs, I. M. "Principles of Communications Engineering", Pg. 436, J. Wiley and Sons, 1965
- 5.4-6 Stiffler, J. J., "The Squaring Loop Techniques for Binary PSK Synchronization," JPL-SPS No. 37-26, Vol. IV.
- 5.4-7 Lindsey, W. C., "Phase Shift Keyed Signal Detection with Noisy Reference Signals," IEEE Transaction on Aerospace and Electronic System, Vol. AES 2 No. 4, July 1966, pp 303-401.
- 5.4-8 Bustamante, H. A., "Optimum Distribution of Power in a PSK Telemetry System," Philco-Ford, VOYAGER Capsule Memo VC-135, November 10, 1966.
- 5.4-9 Goldstein and Kendall, "Low Data Rate Telemetry" pp. 501-506. Proceedings of the American Astronautical Society, Symposium on Unmanned Exploration of the Solar System, February 1965.
- 5.4-10 A. J. Viterbi, "Error Bounds for M-ary Orthogonal Communications Using Stationary Stochastic Signals", JPL-SPS 37-37 Volume IV, pp 262-268.
- 5.4-11 F. J. Charles and N. P. Shein, "A Preliminary Study of the Application of Non-Coherent Techniques to Low Power Telemetry" JPL-TM No. 3341-65-14, November 15, 1965.
- 5.4-12 A. J. Viterbi, "Performance of an M-ary Orthogonal Communication System Using Stationary Stochastic Signals," IEEE Transactions on Information Theory, July 1967.
- 5.4-13 M. J. Ferguson, "Low Data Rate MFSK Using a Slowly Varying Frequency and Constant Phase Signal", VOYAGER Internal Memo, VC-209, Philco-Ford SRS, May 1967.

- 5.4-14 Viterbi, A. J., "MFSK Analysis", Submitted to Philco-Ford.
- 5.4-15 Greenspan and Chesler, "Application of Statistical Principles to the Detection of Weak Signals in Gaussian Noise", Res. Report N-456, Sylvania Applied Research Lab, Waltham, Mass., 31 March 1967.
- 5.4-16 M. J. Ferguson, "VOYAGER Surface Laboratory Trade Study on the Optimum Receiver Configuration for the Detection of Low Data Rate MFSK," VOYAGER Internal Memo VC-277, August 1967.
- 5.4-17 "Single Channel Cross Multiplier Spectrum Due to Input Noise," by R. E. Frary, JPL-TM-3341-65-9, June 1, 1965.
- 5.4-18 Spilker, J. J., "Delay Lock Tracking of Binary Signals," I.R.E. Trans. on Space Electronics and Telemetry, Vol. SET-9, March 1963, pp 1-8.
- 5.4-19 Kraus, J. D., Antennas, McGraw-Hill Book Co., 1950.
- 5.4-20 D. Haccound, "Simulated Communication with Sequential Decoding and Phase Estimation," S. M. Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts. September 1966.
- 5.4-21 1973 VOYAGER Capsule Systems Constraints and Requirements Document Revision 2. Jet Propulsion Laboratory, Pasadena, California, 12 June 1967.
- 5.4-22 "Review of Alternate Multiplexing Techniques", Philco-Ford Corporation, VOYAGER Capsule Memo VC-186.